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NAVAL POSTGRADUATE SCHOOL
Monterey, California

A CHRONOLOGICAL STUDY OF THE MEASUREMENT OF THE OPTICAL PROPERTIES OF OCEAN WATER

and

AN ATLAS OF THE DIFFUSE ATTENUATION COEFFICIENT, k, OF TROPICAL ATLANTIC OCEAN WATERS

Donald A. Stentz
Associate Professor of Electronics

June 1975

Technical Report

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ABSTRACT

This report is a chronologic study of the measurement and methods of presentation of certain optical parameters of sea water. Of particular interest is the diffuse attenuation coefficient, k, and its relationship to the Secchi depth and the temperature profile of the water column. An Atlas of the diffuse attenuation coefficient for the tropical Atlantic Ocean is presented. The report contains some conclusions regarding these relationships and methods of presentation of optical data as these apply to the ORICS program.

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FOREWORD

This study was made for the purpose of determining what optical measurements have been carried out in sea water that would be useful to the ORIC program. The optical characteristics of sea water have been of interest to the fishing industry primarily because the transparency of the sea water is often related to the amount of nutrients contained and, therefore, the variety, amount, and whereabouts of fish life in the water column.

For many years the optical property, transparency, was measured with the Secchi disc. This 30 cm white disc is lowered in the water until it can no longer be seen by an observer looking through the air-water interface directly above it. This optical measurement has been quite effective for its purposes, however it is felt to be too crude a measurement for determining the depth at which a dark object could be seen beneath the surface when illuminated by artificial light.

Another optical measurement that has been made for many years and that would better serve the above purpose is the diffuse attenuation coefficient, k. This measurement is taken with a photometer (k or irradiance meter) and as the Secchi disc method, used the sun and sky light as the source of light. Light intensity measurements are generally taken to depths where 1 to 0.1 percent of the surface light yet remains. Most of the data available have been taken by the Fisheries, and little record exists that indicates the type of meters used, their calibration, wavelength, or bandwidth. Since the measure-

ment for determining k would be more easily standardized than the Secchi measurement, it is felt that this optical parameter would be more useful to the ORIC program. The relationships between k, Secchi depth, and other optical and physical parameters such as temperature profile of the water column are reported on. An Atlas of the diffuse attenuation coefficient has been made for the tropical Atlantic Ocean. Methods for displaying diffuse attenuation coefficient with depth have been identified and a format is suggested that indicates both horizontal and vertical variation of k in selected waters. Some recent research for predicting the optical properties of the water column through a measure of the spectral characteristics of the radiated light from the surface and a radiation transfer model is also reported on.

1. EARLY ATTEMPTS TO MEASURE LIGHT PENETRATION IN OCEAN WATER

a. Blue-Green Window

In 1932, Utterback (1) reported on the attenuation of light in the waters off southern Alaska. He used sun and sky light as the source of irradiation in making his measurements. His graphs plot log intensity against depth, thus the slope of the curve is the diffuse attenuation coefficient, k for the column of water. He used the term "absorption" which is only one of the two mechanisms by which the light is attenuated, the second being scattering. Utterback's measurements were made by using photometers sensitive to the green, blue and red portions of the spectrum. Most generally the spectral characteristics of this photometer overlapped considerably, making it difficult to interpret the data for any single spectral value. He was able to show that the least "absorption" of solar light (sun plus sky) occurred somewhere in the blue-green region, and that depending upon the specific water characteristics was sometimes predominantly blue and sometimes green. He attempted to discover the reasons for the shift in the apparent "window" by relating the physical characteristics of the water such as salinity, particulate count, color, and temperature.

b. Apparent color of the ocean.

Utterback concluded that "the observed color of the water is due to the light which has been scattered at the surface", and "also it is due to the light which has penetrated beneath the surface scattered by inequalities in the water, and reflected to the eye of the observer after having passed through a layer

of water where it is deprived of some of its spectral components by absorption." "Greater transparency in the blue-green region should be expected far out in the open ocean where the greenish tint of inshore water is replaced by blue ocean water." He did not identify those components responsible for this absorption of certain spectral lines and which gives rise to the apparent window.

c. Absorption of Light by Yellow Substance.

It was not until later that Jerlov and Picard (8, 1958) and Gilbert (9, 1968) identified the yellow substance in certain ocean water and determined that it was responsible for the absorption of solar light.

Measurements taken by Utterback were for the purpose of calculating the diffuse attenuation coefficient, k, characterized by Alaskan water. His data were compared with those obtained by Atkins taken at the International Hydrographic Station E-1 (English Channel). The two waters appeared to have similar values of k, however, the Alaskan water had maximum transparency in the blue region, whereas Atkins reported maximum transparency in the green portion of the spectrum.

2. LACK OF GOOD INSTRUMENTATION AND EFFECTIVE CALIBRATION

There is a distinct possibility, of course, that the photometer spectral characteristics used by each observer were different. However, Utterback and Boyle (2, 1933) went on to make measurements near the San Juan Archipelago and discovered that in that region the spectral window had shifted from the blue to the green when compared with his earlier efforts. Utterback

and Boyle identified the spectral sensitivity of their Helland-Hansen type photometer fitted with filters as: Red (600 nm-700 nm). green (500 nm-590 nm), blue (410 nm-500 nm). Even within these fairly broad spectral bandwidths they were able to observe daily changes in attenuations of light. Not all changes in log intensity were exponential when plotted against depth. They concluded, as did Beebe, that the maximum transmission is in the blue portion of the spectrum for open ocean, and at least for water at the northwest Pacific, the greatest deviation for true exponential attenuation occurred for wave lengths somewhere between 563 nm and 529 nm. It was also apparent that the deviation away from true exponential absorption depended upon the volume content of the photosynthetic zone and upon impurities which were the result of river and glacier runoff. It should be emphasized that all of these measurements were taken in inshore waters. It was not until years later that sufficient deep ocean measurements were taken to establish the definite differences in the transparency of inshore and open ocean waters.

3. DIFFUSE ATTENUATION COEFFICIENT, k, DETERMINED FOR CERTAIN SPECTRAL REGIONS AND IN VARIOUS KINDS OF OCEAN WATER.

a. Early Attempt to Classify Water

In 1934, Oster and Clarke (3) investigated the penetration of red (600 nm-700 nm), green (490 nm-620 nm) and violet (310 nm-450 nm) light in three distinctly different Atlantic waters. These regions were the Sargasso Sea, Woods Hole, and Gulf of Maine. They classified the first as deep ocean, the second as coastal water, and the third as sheltered inland water.

This was an early attempt to classify ocean water in categories related to land mass, bottom contour, and depth. Many such attempts have been made with only partial success.

b. The Diffuse Attenuation Coefficient, k.

These researchers proposed to make a careful comparison of these waters with respect to their transparency, and their relative power to attenuate certain spectral wavelengths. The blue spectral data, missing from the bands given above, had been collected during a previous series of measurements. Thus the blue data may or may not typify the water transparency to blue light at the time this new series of tests were made. It is interesting to note that at this time it was also decided to take data to a depth where 0.01% of the surface irradiance yet remained. From these measurements it was easy to calculate the integrated diffuse attenuation coefficient for the depth where any given percent of surface light remained.

$$k = \frac{\log_e \frac{I}{I_o}}{Z} (m^{-1})$$

I_o = surface intensity, I = intensity at the depth where 0.01% of the light intensity remained, and Z the depth in meters.

Figures 1a through 1d are representative of their plotted data.

Judging from the irregularity of plotted points on the curve, the photometer was lowered to some depth, the light intensity measured, and a plot made. k was determined for various points on the curve that represented changes in the transparency

of the water at that depth. Thus the layers can be observed as well as the general transparency of that station to blue, green, violet, or red light.

c. Additional Water Types

These plots suggest that at least for the water being measured, deep water at the Sargasso Sea (Fig 2b) was more transparent to the blue than violet or green, whereas for the Gulf of Maine (Fig 1a) green indicated the smallest value of k. Oster and Clarke concluded that waters could be identified as slope, continental shelf, gulf stream, coastal, and inshore water. They postulated that particulate matter both organic and inorganic would reach equilibrium somewhere between the surface and deep water and that this cloud of particles would most likely be suspended at the thermocline. It was apparent that the selective transparency of the water column was a result of the light passing through this layer being absorbed and scattered in accordance with the optical properties of the particulate matter. Particulate matter alone is not responsible for the total attenuation, however.

4. ATTENUATION OF LIGHT BY ABSORPTION DUE TO DISSOLVED ORGANIC SUBSTANCE.

a. Yellow Substance

Jerlov (4) described the "yellow substance" actually responsible for attenuation by absorption as a substance formed from free carbohydrates and free amino acids caused by disintegrating organic matter. Clearly then, water containing a high degree of organic material will contain a larger amount of this

substance and will absorb light accordingly.

b. Absorption of Light Wavelength Dependent

By 1960, Jerlov attempted to further classify ocean water according to its optical properties. Fig 2a shows Jerlov's curve for absorption plotted against wavelength. It is seen that for wavelengths above 600 nm, absorption is at a minimum, and for the shorter wavelengths becomes a major factor. From this alone one could conclude that the shorter wavelengths (blue and green) should be more highly attenuated and thus the "window" should appear in the longer wave length region. He, however, studied the effect of the above mentioned particulate layer and concluded that scattering caused by organic particulate matter is virtually independent of the wavelength, and the total attenuation for the blue-green region was less than for the longer wavelengths. Absorption, on the other hand, is sharply dependent upon wavelength and is a function of the resonant processes within the molecules of water and other substances in solution.

5. SCATTERING OF BLUE LIGHT MOSTLY IN THE FORWARD DIRECTION.

In order to reach the above conclusion one must examine Fig 2b for the volume scattering function for ocean water for blue light. We see that most of the scattering is in a forward direction. Thus this "amplification" through scatter in the forward direction appears to overcome the larger absorption levels in the blue-green region. Jerlov concluded that the particle size in water that he tested is large compared to the wavelength of blue light, suggesting a particle size on the order of 10μ. Scattering function measurements taken by earlier observers

indicate close agreement with Jerlov's data. He concluded that the particulate characteristics in the ocean seemed to be an essential factor for classifying ocean water. He points out that there is a relationship between the number of organic particles per unit volume and the amount of yellow substance. Fig 2c relates various geographical waters to the total scattering coefficient and the irradiance attenuation coefficient, k, for a slab of water 50 meters deep at the wavelength of blue light. From this curve it is easily concluded that Galapagos Islands are high in particulate matter that scatters the blue light and very high also in yellow substance. At the other extreme, the Sargasso Sea is low in scatters and low in yellow substance since the irradiance attenuation is also small.

6. CLASSIFICATION OF OCEAN WATER BY THE PERCENTAGE OF SURFACE IRRADIANCE PLOTTED AGAINST DEPTH FOR A SINGLE SPECTRAL WAVELENGTH.

a. Jerlov's Water Types

Jerlov then classified ocean water as indicated in Fig 2e. Classification I indicates highly transparent water at 465 nm ($k = 0.0325$) while type III is less transparent water having a k in the vicinity of 0.115. Since values of k have been measured far in excess of 0.115, it follows that yet a fourth classification can be added to his list, namely, turbid water. Fig 2d reveals yet another characteristic of importance when classifying ocean water. Type I (clear water) transmittance is greatest in the blues, while Type III tends to peak in the greens. It is clear that one characteristic of the column of ocean water is

that it acts as a filter of solar irradiation. If one then relates the observed color of the ocean by an observer in an airplane to Fig 2d, there seems good reason why the radiant light from the surface (upwelling light) should appear blue at one location and green at another, depending upon the particulate matter and yellow absorbing substance contained in the column of water.

b. Turbid Water

More recent measurements in various oceans suggest at least five optical classifications of ocean water.

Type of Water	Equivalent Jerlov Classification
Dirty water (Turbid)	None
Coastal Waters	III
Cool and shelf waters	II
Warm ocean waters	IA & IB
Clearest ocean waters	I

It is difficult to describe each of the above water types in terms of their biological, chemical, and physical makeup. It is clear, however, that there is a wide range in quality as the percentages of these components change. Dirty water is generally observed around sea shore, inland bays, and river mouths. Undoubtedly, much of this turbidity can be attributed to inorganic suspended matter. This matter is generally well distributed due to the mixing action of waves, currents, etc. Probably the attenuation is more dependent upon scattering than absorption. Waters near the Continental Slope or in regions of great upwelling are often rich in organic substance and appear dirty by particle count, but

actually may be quite clear optically. If, on the other hand, these waters are also high in yellow substance, then attenuation may be great and frequency sensitive. Clearest ocean water contains almost no inorganic or organic scatterers. Yellow substance does not enter the region except by ocean currents. Thus this water is highly transparent approaching that of distilled water. [Duntley 21].

7. DIFFUSE ATTENUATION COEFFICIENT OF DEEP OCEAN WATER AND REGIONS OF STRONG OCEAN CURRENTS.

In 1936 and 1937, Clarke (5) made tests for light penetration in the Caribbean Sea and the Gulf of Mexico. Previous measurements had been conducted in coastal waters and inshore areas chiefly in the Northern hemisphere. During these tests he obtained data for the open ocean and regions where high currents prevailed. His photometer was a Westinghouse photo cell having a maximum spectral sensitivity at 550 nm, with a 10% drop off at 465 nm and 625 nm, respectively. Even though the spectral width was quite broad, he noted that the logarithmic plots of intensity measurements made in a homogeneous body of water were remarkably straight and concluded that discrepancies introduced by the broad bandwidth were of negligible proportions. Measurements were plotted as percentage of surface intensity against depth as before (see Fig 3a-c). The clearest water was found in the Cayman Sea west of Jamaica where the integrated value of k was 0.038. This clear water occurred in a layer from 95 meters to 185 meters in depth. The value of k for the entire water column averaged 0.042 at 185 meters, where 0.035% of the surface intensity yet remained.

Figs 3a-c are examples of his data and indicate the spectral filter characteristic of the water column and the regions where definite variations in transparency occur. No variations in spectral attenuation can be seen because of his use of a broad-band photocell.

8. ATTEMPTS TO MAKE MEASUREMENTS OF OPTICAL PROPERTIES OF OCEAN WATER FROM SAMPLES TAKEN TO A LABORATORY.

By 1938, Clarke (6) felt that it might be possible to take samples of the ocean water and in a laboratory to make measurements to determine its optical transparency. These efforts were not successful because the characteristics of the sample changed during the long period between collection and testing. Particulate matter settled, organic material died, and it was easy to contaminate the sample by using containers that dissolved in the ocean water. He did succeed, however, in showing that filtered sea water, regardless of where it came from and as long as it did not contain yellow substance, attenuated the visible spectrum about the same as distilled water. Based upon these measurements, he predicted that maximum penetration of light into ocean water should occur in the blue region. He showed that with greater depth the ocean generally became more transparent. Most of the plots of percentage surface intensity versus depth seem to bear this out.

9. OCEAN ACTS AS A FILTER OF NATURAL LIGHT - ONLY BLUE LIGHT REMAINS AFTER MORE THAN 100 METERS IN DEPTH.

In 1956, Burt (7) attempted to repeat Clarke's experiments but this time he performed the measurements to determine trans-

parency within one hour after surfacing the sample. His tests were made at fifteen eastern tropical Pacific Ocean stations at depths from the surface to 1170 meters. A Beekman Model DU Quartz Prism Spectrophotometer was used. The instrument readings were converted to percentage transmission per meter, and the extinction coefficient, k, calculated. In general, even though Burt's method of measurement differed from Clarke, Utterback, Jerlov, Sawyer, and Poole, he found agreement with their data. He pointed out that at greater depths the natural hardening (band limiting filter effect) of natural light does occur, and that for depths greater than about 100 meters, only the blue light remains. He also noted that his data agreed with that of previous experiments which indicated that a surface layer of relatively turbid water usually existed over a more transparent water. This layer rarely extended more than 100 meters in depth. It would appear that only the first 100 meters of water need be measured for transparency, and that for most measurements reported, the remaining percentage surface light intensity is 0.01% or more even for coastal waters of sufficient depth.

10. OBSERVATION OF OPTICAL PROPERTIES OF THE OCEAN FROM A BATHYSCAPH.

Yet another method of measuring the water transparency was carried out by Jerlov and Picard (8) in 1958. They studied the penetration of light in the blue regions of sun and sky light to depths of 300 meters making use of the bathyscaph; Trieste, off Capri. Their results show the gradual increase in daylight extinction from the surface to 100 meters. Where deep layers of

particulate matter existed, the extinction was much greater than what they termed "typically clear water". They found that the peak of the transmitted irradiation occurred at 481 nm. Below 200 meters the light was sufficiently monochromatic that a filter was not needed. In the offshore water of the Tyrrhenian Sea about 0.00024% of the surface light remained at a depth of 300 meters. The average diffuse attenuation coefficient, k, for that depth was 0.039. Jerlov noted that such a high transparency existed only when the water was free of yellow substance and when the plankton population was low. Considerably greater values of k were observed when measurements were taken in water where particle count was high, this occurring generally near submarine slopes.

10. IDENTIFICATION OF THE COMPONENTS OF OCEAN WATER RESPONSIBLE FOR ATTENUATION OF LIGHT.

a. Components of Attenuation

Gilbert (9) made an analysis of the attenuation of light in sea water in 1968. He was interested in identifying the various components of water that were responsible for attenuating the light in certain spectral regions. He defined the ocean water as consisting of "pure" sea water in combination with dissolved organic substances (Jerlov's yellow substance) and suspended organic and inorganic particulate matter. Hence, the light attenuation coefficient should be expressed as:

$$\alpha = \alpha_w + \alpha_s + \alpha_p$$

where α_w is the attenuation due to "pure" sea water,

α_s is the attenuation due to dissolved organic matter,

α_p is the attenuation due to particulate matter.

Furthermore, any particular attenuation coefficient can be further subdivided into:

$$\alpha_i = a_i + s_i$$

where a_i is the attenuation due to absorption,

s_i is the attenuation due to scattering.

For "pure" sea water,

$$\alpha_w = a_w + s_w$$

a_w for "pure" sea water has greater effect due to molecular absorption than s_w, the effect of molecular scatter.

b. Relative Effects of Absorption and Scatter

Gilbert (9) found that only at a wavelength of about 460 nm is scattering in "pure" sea water the same order of magnitude as the attenuation due to absorption. For wavelengths greater than about 580 nm, the extinction of light due to scatter is less than 1%. The dissolved organic substance causes greater absorption at the shorter wavelengths and tends to shift the "pure" sea water maximum at 460 nm toward the green region of the spectrum. Thus blue light in "pure" sea water would penetrate to greater depth as Jerlov and Picard found. It has been estimated that there is three to ten times as much dissolved organic substance as live organisms in the ocean, thus absorption plays a major role in the transmission of light. If one considers only the particle contribution to volume attenuation, of major importance is scattering. Tyler (16) states that the absorption

of light by naturally occurring organic particles can be ignored in fact. Gilbert feels from the foregoing that a reasonable model of the volume attenuation coefficient for natural ocean water is:

$$\alpha = a_{w+s} + s_p$$

where a_{w+s} is the attenuation in "pure" sea water due to absorption and scatter. s_p is the attenuation due to scatter caused by particulate matter, presumably chiefly inorganic in nature.

c. Most Attenuation occurs in the First 100 Meters.

Gilbert's calculations agree rather well with those taken by other researchers for a number of geographically different waters and for a wavelength of 490 nm. His plot for three different regions indicate that most of the attenuation occurs from 0 to 100 meters. At depths below 100 meters the curve is nearly flat. He found that waters around the Aleutian Islands are very turbid for the first 100 meters compared with waters around the Hawaiian Islands. Finally, the California Channel waters have either a dissolved organic substance or suspended matter that is neutrally buoyant at about 50 meters.

11. EFFECT OF OCEAN WATER ON ABSORPTION AND SCATTERING OF COHERENT LIGHT.

Since nearly all of the researchers used the sun and sky light to measure the diffuse attenuation coefficient up to 1968, the question of the behavior of a collimated light beam as a source seemed appropriate to ask. Kullenberg (10) studied the scattering of light by Sargasso Sea water at two wavelengths,

632.8 nm (red) and 460 nm (blue). He found that the volume scattering function for blue light was considerably greater than that for red light for scattering angles greater than 20°. For angles less than 20° there were no differences. This, he concluded, suggests that the molecular part of the total scattering effect is rather important for a large part of the visible spectrum. Comparison of his data with other observers seems to confirm that most of the wavelength dependency is a molecular effect. The forward particle scattering appeared to be virtually independent of wavelength. Although Kullenberg did not report on total attenuation of the laser light in sea water, his volume scattering function appears to agree well with data taken by others who used solar light as a source. There seems to be nothing unique in the attenuation of the laser beam through a column of ocean water. This is probably because the collimated laser beam quickly becomes a diffused light as it passes a few attenuation lengths through the water.

12. THE OCEAN WATER ACTING AS A SPECTRAL FILTER OF LIGHT PENETRATING ITS DEPTHS.

By 1971, Yura (11) quantitatively analyzed small angle scattering of laser light by ocean water. He concluded that there were two mechanisms that give rise to scattering. There are the suspended biological particles having an index of refraction close to that of water and the refractive effects due to large-scale index of refraction variations. Large-scale means large compared with laser beam diameter. For long propagation paths (>10 meters) suspended particles can degrade the transverse coherence properties

of the laser beam much more than do the large-scale refractive index variations. The attenuation of light by sea water as stated by Gilbert, is due to absorption and scatter. Yura contends that α thus determines the gross energetic properties of a collimated light beam as a function of propagation distance. The essential parameters that describe the small-angle scattering are mean size, refractive index, and the concentration of the suspended particles, as well as the length of the path the photon travels without being deviated by any type of scattering, and the absorption process acting in conjunction with the mean square deviations of the refractive index. These relationships are complicated and are not well understood. Whether or not the collimated laser beam will be affected by the mechanisms stated above may well be a function of the beam diameter and its energy level. Considerable analytical and experimental work is presently being carried on by numerous researchers, both here and abroad. Much of this work, however, is being done in an aerosol rather than a hydrosol environment. These efforts may eventually determine such effects as shear (windage), and defocusing or focusing of the laser beam in the aerosol portion of the ORAD propagation path, if not in the water portion of the path.

13. PREDICTION OF RANGE FOR AN OPTICAL RANGING SYSTEM (LIDAR) OPERATING IN THE BLUE-GREEN REGION OF THE SPECTRUM.

a. Predicted Range of Lidar.

In 1963, Mutschlecner, Burge, and Regelson of NOTS (12) predicted the minimum and maximum range one could expect from a laser radar operating in the blue-green region of the spectrum

when the propagation path was all water. Minimum and maximum ranges were determined by the maximum and minimum extinction coefficient for ocean waters as measured by the various researchers reported on elsewhere in this paper. Also, of course, assumptions had to be made concerning a realizable laser beam intensity, the sensitivity of the receiving sensor, and noise level in the form of background light inherent in the water column. Although it is suspected that many other parameters and effects should be included in their analysis, it is interesting to note that range in clear water appeared to be of the order of 1000 meters for presently obtainable laser power. Fig 4a indicates that for the more transparent water the blue light spectrum is superior to the green light. This indicates that a laser whose wavelength was variable, thus capable of matching the window for the water type, would improve range and/or signal to noise ratio.

b. Upwelling Light Scatter Dependent

When solar radiation illuminates the surface at the sea, some of the downwelling light is absorbed and scattered in the water column. A small portion is back scattered toward the surface and is returned to the atmosphere. The intensity of the returned light (upwelling) appears to depend upon the scattering characteristics of the water, the spectral absorption, the bottom if shallow water, and surface where the greatest change in refractive index occurs. Of importance also is the albedo of any surface within the water column whether it be an opaque surface or merely a large volume having different refractive characteristics due possibly to suspended particulate matter, temperature changes, currents, etc.

14. SPECTRAL IRRADIANCE OF UPWELLING LIGHT FROM THE OCEAN.

Stamm and Langel (13) investigated some of the spectral irradiance characteristics of upwelling natural light off the east coast of the United States. They pointed out that Hulburt [21] derived equations which calculated the spectral distribution of light flowing upward when certain optical constants of the water and spectral characteristics of the light were known. These calculations indicate the filtering effect of the water column and give some indication of absorption and scatter. From this insight it seems reasonable to assume that the observed color of the water (observed vertically downward from some height above the surface) could give an indication of how light is attenuated and what particular spectral wavelengths are most affected. Stamm and Langel state, "As far as we know, there are no references to measurements of the spectral distribution of upwelling light from the sea; the spectrum of this upwelling light will affect albedo measurements when optical sensors having different spectral sensitivities are used." Earlier studies by Powell and Clarke showed that from three to nine percent of this incident light is reflected and scattered back into the atmosphere.

15. CLASSIFICATION OF WATER BY COMPARISON WITH THE FOREL SCALE.

An attempt has been made to classify the absorption and scattering characteristics of ocean water by comparing visually the upwelling light with a standard Forel scale of eleven colored liquids. These vials contain ammoniacal copper sulphate and neutral potassium chromate in such proportion to impart a particular color spectrum to each of the eleven vials. Selection of

the color which matches the upwelling light gives some measure of the amount of absorption and scatter suffered by the sun and sky light as it passes through the water column. It is not inconceivable that some knowledge of the spectral characteristics and, therefore, the amount of absorption and scatter can be made by measurement of the upwelling light as Stamm and Langel suggest.

Figures 5a-d reveal some interesting characteristics of different waters and depths. There are striking differences between deep and shallow water. They concluded that differences in absolute spectral irradiances measured from one place to another under various sea surface and atmospheric conditions are obvious, however, the factors which cause the differences are difficult to separate. They were unable to take measurements that systematically separated the various effects upon the upwelling light.

16. <u>USE OF RADIATIVE TRANSFER THEORY, AND OPTICAL PROPERTIES OF OCEAN WATER TO PREDICT THE COLOR OF THE WATER WHEN OBSERVED FROM SOME HEIGHT</u>.

a. Remote Sensing of Optical Properties of Water Column.

In a recent paper written by McCluney (14) remote sensing of the optical properties of ocean water seems much nearer than Stamm and Langel were able to show. Large-scale models of the optical properties of the ocean water have been postulated. From these models and a new radiative transfer theory suggested by Gordon and Brown (18) for determing the upwelling spectral radiance emerging from the sea, McCluney has contrived a quantitative way of predicting what the optical properties of the water column are. He must know certain things about the water column, such as

the absorption and scattering coefficients, depth, etc. In order to try his technique, he used data prepared by Kullenberg (10) for the Sargasso Sea, and incident irradiance predicted by an atmospheric model for clear atmospheres developed by Curran (19). For this case he used his Quasi-single scattering model to predict the magnitude (intensity) and wavelength of the upwelling light. Fig 6b compares the theoretical upwelling irradiance spectrum with upwelling irradiance data collected by Hovis (20). Excellent agreement can be seen considering the fact that the data were taken by a number of observers at different times and places.

b. Rapid Measurement Method.

McCluney feels that his method is just as valid for turbid water. It would seem that by making use of his method a measurement of the spectral characteristics of the sea by actual observation should reveal the optical characteristics of the water column, i.e., the reverse of McCluney's procedure. If this were true, could his method be used to ascertain the optical properties of the ocean much more quickly than the present method of point by point measurement? Furthermore, is it not possible that seasonal changes, characteristics and depths of turbid layers, bottom conditions, and other anomalies could also be predicted?

17. <u>INVESTIGATION OF THE EFFECT ON A LASER BEAM FROM SCATTERING PARTICLES IN OCEAN WATER, AND ESTABLISHING THAT THE DIFFUSE ATTENUATION COEFFICIENT, k, IS CORRECTLY USED FOR LASER BEAMS TRAVELING REASONABLY LONG RANGES.</u>

Measurement of the diffuse attenuation coefficient, k, of ocean water has generally used the sun and sky light as the

irradiative source. Okoomian (15) investigated the transmission of an intense, narrow-beam, coherent radiative source. This was a laser operating at 530 nm having a bandwidth of 2.4 nm. By restricting the field of view of his receiver he was able to show that for longer ranges (>30 attenuation lengths) the forward scatter of the high intensity beam increased range considerably. When the field of view was but 2° he found that this excluded the multi-path irradiance which seemed to suggest that the collimated beam is scattered with the photons not re-entering the 2° field of view. On the other hand, when the field of view was opened to 26°, scattered photons were eventually directed back into the beam and reappeared in the wider field of view. This caused a noticeable increase in the irradiance measured. He concluded that for extended ranges, the total irradiance function, H_t, is approximately equal to H_r^*, the multi-path irradiance, and that the correct exponential factor to use for this case was k rather than α, the attenuation constant in which only mono-scattering is considered. Thus it seems that the use of the relationship

$$I = I_o e^{-kZ}$$

is correct for both the diffuse source and a laser source when range is extended. Duntley (21) observed this forward scatter phenomenon with both natural light as a source and for a point source (lamp). He also ascertained that the diffuse attenuation coefficient, k, (scattered light) is always less than the volume attenuation coefficient a, (non-scattered light) by a factor of 2 to 4 at the wavelength of maximum attenuation lengths. The

mean value of the ratio a to k for clear, natural water is about 2.7.

18. RADIANCE DISTRIBUTION OF NATURAL LIGHT IN OCEAN WATER.

Tyler (16) investigated the radiance distribution as a function of depth in an underwater environment. He used the sun and sky light as his source, however, he limited the bandwidth of the photometer to the blue-green region. He surmised that the radiance distribution in an optically deep and homogeneous hydrosol would approach a characteristic shape with increasing depth. Preisendorfer had developed a proof of existence of asymptotic radiance distribution which showed that the final shape depends upon the spectral properties of the hydrosol, specifically, the volume scattering function and the absorption coefficient. If the absorption coefficient approaches zero with depth, a fact borne out by previous researchers, the asymptotic radiance distribution tends to become a sphere. On the other hand, if the scattering function approaches zero, the final shape would approach a vertical line. Since neither of these functions is ever zero, it is reasonable to assume that the shape of the radiance distribution is somewhere between the sphere and the vertical line. All this seems to suggest that the illuminated volume of water varies as the optical properties vary, and that for water such as that of the Sargasso Sea, the shape of the radiance distribution may be deep with narrow cross section, whereas, for water having a large number of scatters, the cross section illuminated may be much larger. Since, according to Okoomian, the laser beam acts strongly like diffused sun light after traveling a few attenuation

lengths, it follows that the beam diameter of the laser beam may change as the optical properties of the water column change.

19. USE OF MONTE CARLO AND MIE THEORIES FOR PREDICTING INTENSITY OF THE RETURNED IRRADIANCE FROM A TARGET HAVING LOW REFLECTANCE

a. Statistical Methods Used.

A knowledge of the distribution of the photons emitted as a pulse of radiation from a laser, and subsequently scattered by the hydrosol would provide important information about the properties and spatial distribution of the particles. Kattawar and Plass(17) contend that theoretical guidance in these problems has not been forthcoming because the radiative transfer equations are not yet available when the source is a narrow high intensity beam from a laser. These researchers have applied the Monte Carlo method to find the interaction of the photons of the laser beam with the water molecules and other scattering particles. The probability that scatter will occur through a particular angle was determined by the MIE theory. In their study, the receiving detector is located at the source, as in the case of the ORAD System. They were thus able to generate curves of returned flux plotted against photon path length for different surface albedo where the target is located at different depths.

b. Range Limited Only by Sensitivity of Sensor.

The conclusion that they reached was that when the surface albedo of the target was greater than 0.02 (2%) it can be detected at any distance by a measurement of returned flux from the laser beam as a function of the photon path length. From the practical point of view, the range was really limited by the sensitivity of

the receiving sensor and the amount of noise caused by background ocean light and sky light getting into the receiver. Their calculations indicate that in an optically homogeneous ocean it would be possible to measure changes in either the magnitude or slope of the returned flux curve, and to interpret these changes as either albedo or attenuation variations within the column of water.

20. RECENT EFFORT IN OBTAINING k DATA

a. EQUALANT Data

During the period from 1963 to 1964, a concerted effort was made by the Intergovernmental Oceanographic Commission to determine the transparency of tropical Atlantic waters. One of the purposes of this study was to determine to what extent these waters supported biological life, and thus how productive this area would be for fishing purposes. The data were collected through the cooperative efforts of many nations, World Data Center, and the Food and Agricultural Organization. The National Oceanographic Data Center processed the measurements taken and prepared the tables and charts. This study was called "The International Cooperative Investigations of the Tropical Atlantic, EQUALANT I, II, III." (25). The measurements were made in either the Spring or Fall of 1963 and 1964. Some seasonal characteristics are evident where Fall and Spring cruises overlap the same area.

b. Method of Reporting Data

In addition to taking the usual physical and chemical oceanographic and meterological data, participants were also to measure the percentage of surface light at depths where 50%, 25%, 10%, and 1% of the surface light intensity yet remained. Measurements

were made by a photometer (k meter), however, some cruises used the Secchi Disc and converted Z_s to k through the Poole-Atkins equation. For purposes of this report, k data obtained by using the Secchi Disc were ignored. Generally, measurements were made down to the 1% intensity level. Thus the method of taking and reporting the transparency data was uniform, and furthermore, similar to measurements taken by Utterback, Clarke, Jerlov, and others.

c. Waters Involved in the Data Collection Effort

EQUALANT measurements were made over a wide expanse of the tropical Atlantic from South America to Africa. Fig 7 shows that data were taken in a 30° belt centered on the Equator extending from South America to Africa. On the South American side the Orinoco and Amazon Rivers pour millions of tons of silt and nutrients into the ocean. These nutrients are used for food by plankton and other forms of sea life. These waters are strong absorbers, as well as scatterers, of sun and sky light that penetrate its depths. A similar situation occurs off the African west coast due to the run-off of the Sengal, Niger, and Congo Rivers. One would expect that the transparency, as well as the apparent color of the tropical Atlantic, would reflect these facts. In Fig 7 each black dot indicates a point of measurement (station) where the light intensity down to 1% of the surface light intensity was measured. Contours were plotted for each 0.01k (diffuse attenuation coefficient) interconnecting the various cruise areas.

d. Graphs and Charts of EQUALANT Data

Figs 8 - 13 are plots of some of these data. The slope of

the curve indicates the diffuse attenuation coefficient, k, for each segment of the water column measured. The maximum and minimum values of k down to the 1% level for each cruise plotted are indicated. The point of measurement (station number) on the graph line is also shown on the cruise chart, Fig 14. The dashed line on each graph represents the value of k for distilled water (0.024 at 540 nm). Obviously, no segment of the curves for that station can exceed the slope of the distilled water, and generally, even the most transparent sea water will not exceed an average water column value of k equal to 0.038 as reported earlier. It is seen, however, that some segments of the water column approach the slope of the distilled water curve. For example, station 63 of the EXPLORER cruise, Fig 9, in the segment of water between 24 meters and 60 meters. Changes in the slope indicate variations in k caused by absorption and scattering changes, and perhaps changes in the refractive index or other optical properties of the water column. It seems possible, as reported by McCluney (14,23), that as the photometer measures the changes in light intensity with depth, the reflected or backscattered light from the water column would also reveal some of these optical properties when viewed from above the surface of the water. The sunlight is filtered along both its incident and reflected paths, thus the apparent color of the water should indicate this. Clear, deep water is generally deep blue indicating that the greens, reds, and yellow spectral line have been filtered out. Shallow, less transparent water, reflects the bottom optical characteristics, as well as those of the water column.

e. Classification of Ocean Waters

Fig 15 depicts the water transparency when broadly defined by the following types of water:

Water Type	Increment of k associated with type
Dirty or turbid	> 0.17
Coastal	0.17 to 0.085
Cool and shelf	0.085 to 0.065
Warm ocean	0.065 to 0.04
Clearest ocean	< 0.04

This chart shows the effect river water has at great distances from shore. It is apparent that the water from the Amazon and other South American rivers tends to divide and flow north and south. Waters off the west coast of Africa appear to flow toward the south. Data for this chart were taken for both Spring and Fall seasons and are an average for the year. Not enough seasonal data existed to get good seasonal transparency characteristics except for one area off the west coast of Africa just below the Equator. See charts for the OMBANGO cruises, Figs 10 and 11.

f. Relationship of k and Secchi Depth, Z_s, Data

In order to show the relationship between k for the various types of waters and Secchi Depth, a new relationship derived from measurements taken in various waters by Mr. John Shannon of Naval Air Development Center, Johnsville, PA, and others, were used. As will be seen, most of the simultaneous k and Secchi Depth measurements were taken in water less transparent than many areas of the Atlantic and Pacific Oceans. The relationship derived by Shannon, however, is a good fit for most coastal type water and

some clear, deep water. Previous to this new relationship, k and Z_s were related by the generally accepted Poole-Atkins equation. This relationship is an average of a wider range of water types. The new relationship has been plotted in Fig 16. N represents the correlation factor of Secchi Depth, Z_s, and Diffuse Attenuation Coefficient, k, and is reasonably accurate for Z_s from 4 meters to 37 meters. N plotted on semi-log paper results in a straight line having a value of 1.18 at 4 meters to 2.665 for 37 meters. The interval of k related to this range of N is from 0.295 to 0.07 for the depth range indicated above. By water type previously described, this equation is considered adequate for dirty, coastal, and the clearer half of cool and shelf water types. Since the cleanest ocean water has a value of k equal to about 0.038, some of the water types are not represented by this new relationship. A straight line extrapolation of the curve for k to a depth of about 100 meters would place this curve very near the limiting value of 0:038. This is in accordance with Picard's findings reported earlier in this paper.

g. Optical Attenuation Length

A very recent paper by Gordon and McCluney (23) elaborates on reference (14). This paper indicates water by type as established by Jerlov, and includes nine additional types of water found near coasts. It would appear that Shannon's equation is more appropriate for types 9 through 1 and perhaps, type III. Gordon and McCluney have explored further the depth of penetration of sunlight in the sea for the purpose of remotely sensing water transparency. They describe what they call Z_{90}, the depth

or layer thickness of water from which 90% of the total radiance from the surface originates. For a homogeneous layer of water, $Z_{90} \leq 1/a$, where a is the absorption coefficient of the medium at depth Z. This implies that perhaps the most important effect on the downwelling light is absorption and that for most cases studied by Gordon and McCluney the scattering coefficient, b, had much less effect on the attenuation of both diffuse and collimated light than did absorption. 1/a appears to be a good approximation of the depth of penetration as defined by Z_{90}. The reciprocal of a, called the attenuation length, is the distance which a straight line flow of photons must traverse in order that the scattered power will be reduced by one natural logarithmic unit. (Duntley (21)). They also show that for a given wavelength, Z_{90} is approximately the depth at which the downwelling irradiance falls to 1/e, or 37% of its value at the surface. Since a can be determined only by actual measurement, the depth corresponding to 1/e can be used as a good approximation of one attenuation length for most waters. The vertical red lines on Figs 8-13 make it possible to estimate the average attenuation length for the cruise area or for one station, and furthermore, the number of attenuation lengths to the 1% depth can also be estimated. Since one attenuation length for distilled water is about 41 meters at 540 nm, it is easily seen that most tropical Atlantic waters contain components, presumably those causing absorption in the near surface layer. Gordon and McCluney plotted Jerlov's water types on a graph whose ordinate is Z_{90} (approx. 1/e) in meters and abscissa is wavelength in meters.(see Fig 17). At the wavelength of 472 nm, Z_{90} equals about 55 meters for type I water

(Sargasso Sea water). If a wavelength of 540 nm is used instead, about 20 meters is the depth for Z_{90} this being some better than the average for the Atlantic waters measured. Gordon and McCluney show that for coastal waters the maximum attenuation length at 540 nm is near 8.5 meters and the minimum near 1.5 meters.

h. Comparison of Cruise Area Waters

Fig 14 shows the areas investigated during each cruise. The number at the point indicates the station number and coincides with the number on the slope line of Figs 8 - 13. As indicated earlier, the ratio of the average depths at 37% and 1% surface intensity points is the average number of attenuation lengths the downwelling light passes through in arriving at the lower depth. An attempt was then made to classify the water in the cruise area according to Jerlov's water types in terms of attenuation length. For example, the CASCO cruise indicates remarkably uniform waters to the 37% depth. A uniform decrease in k (from 0.0795 to 0.048) from stations 51 to 121 shows that the water got more transparent as the cruise progressed south, and that the average number of attenuation lengths to the 1% depth was about 8.5. One attenuation length being about 9 meters. In general, these waters can be described as deep ocean possessing optical properties about like those of cleaner, cool and shelf water to that of the less transparent warm ocean water. This region is no doubt affected by the river run-off from both sides of the ocean, however, the graphs show a remarkable uniformity throughout the region of measurement. A similar region occurs in the EXPLORER cruise data. For stations south of 29 the spread of k is substantially the

same as for the CASCO area. However, because the water is considerably clearer near the surface, one attenuation length is longer (10.5 vice 9 meters) causing a reduction of the number of attenuation lengths to the 1% depth to 6.4 In general, unless the water is homogeneous with depth, the optical properties of the water column can not be adequately described in attenuation lengths. Nevertheless, a measurement taken at the 37% depth does indicate the general transparency of the water column. Water beneath this depth is nearly always more transparent judging from plots made of these cruises and those of Utterback, Clarke, and others. Examination of the various graphs show that many water columns have layers of water that are almost as transparent as distilled water.

i. Seasonal Data

In 1963, two OMBANGO cruises were made. The first was in March (see Fig 10) and the second in August (see Fig 11). Since these two cruises surveyed the same area, some seasonal data is evident. Down to the 10% surface light intensity depths these two graphs look very much alike. For depths below the 10% point the two graphs are quite different. In March the water was quite varied from station to station, indicating horizontal differences. The spread was uniform from 0.46 to 0.063. By August, much of the horizontal structure had disappeared. The spread in k was from 0.11 to 0.061 if station 13 is ignored. It can be assumed that river run-off had subsided, some particulate matter had settled and currents and wave action had made the waters more uniform than was the case in the Spring. The average number of

attenuation lengths to the 1% point is less (4.5) due to the inflow of the turbid water resulting in a greater range of k for the area.

21. RELATIONSHIP BETWEEN THE TEMPERATURE PROFILE AND THE DIFFUSE ATTENUATION COEFFICIENT, k.

a. EQUALANT Temperature Profile Data

The EQUALANT report contains some temperature profile and transparency data taken at the same station. These data may not be simultaneous, however, they were taken on the same date. Transparency data were generally taken between 1030 and 1530 since the source of the light for the measurement was the sun and sky light.

b. Characteristic Relationship of Temperature, k, and Depth

Figures 8e and 11e indicate the extremes of the temperature profiles for the CASCO and August OMBANGO cruises, respectively. The individual profiles for the OMBANGO area were all very similar in shape. These are characterized by a surface isocline, a steep negative gradient below this isocline, and finally, a slowly changing negative gradient or a second isocline. Three representative profiles (Figures 11b-d) have been made. To the left of the profile, the value of k has been plotted. Since light intensity data were taken only at depth where 50%, 25%, 10% and 1% of the surface intensity remained, the diffuse attenuation coefficient has been assumed to remain constant within each respective interval. It would have been better if the transparency measurements had been taken contin-

uously with depth so that the fine structure of this parameter would be evident. Even though the data are rough and perhaps not simultaneous, some general characteristics between k and temperature can be seen.

(1) There is always a very turbid (dirty) surface layer four to five meters thick whose value of k runs from 0.07 to 0.17 or greater.

(2) The water column transparency nearly always improves with depth, particularly when there is a deep isocline layer. This layer runs from a few meters to 50 meters in depth.

(3) At the bottom of the surface isocline or in the steep negative temperature gradient region there is nearly always a sharp increase in the value of k. It is interesting that in many cases the water in the isocline improves in transparency with depth and approaches that of the Sargasso Sea water. The particulate matter will generally find neutral buoyancy somewhere near the bottom of the isocline or in the steep portion of the negative temperature gradient. Just where this occurs is dependent upon many factors such as: temperature range of the water, density, size and type of the particulate matter, and for some organic matter, the intensity of the sunlight. Figure 11a should be related to Figures 11b-e. For the August OMBANGO cruise the horizontal and vertical transparency of those waters had remarkable uniformity as indicated earlier.

c. The CASCO Cruise Area Characteristics

Figures 8a-e are a similar set of temperature profiles and k graphs for the CASCO cruise area. Figures 8a and 8e

indicate much less horizontal and vertical similarity in k and temperature profile from station to station than did the OMBANGO area. Three characteristic temperature profiles are required to describe that region.

(1) Type 1, Fig. 8b - Surface isocline layer, over a sharp negative temperature gradient with depth followed by a deeper isocline layer.

(2) Type 2, Fig. 8c - Surface isocline layer, followed by a moderate negative temperature gradient continuing toward the bottom.

(3) Type 3, Fig. 8d - Moderate negative temperature gradient starting at the surface and continuing to a depth of about 50 meters, followed by an isocline region continuing toward the bottom.

k values were again plotted against depth and the same basic conclusions can be made for this area as were made for the OMBANGO area. At some stations, the increase in k at the base of the isocline or in the negative temperature gradient was more dramatic than for other stations; however, the increase in k always existed.

d. General Relationships

From this examination of the relationship between the diffuse attenuation coefficient and the temperature profile it appears that information concerning the change in temperature with depth would be useful for determining the approximate depth where the increase in k could be expected, and from the shape of the profile it appears possible to make some assumptions regard-

ing the sharpness of the increase in k. Since the amount of attenuation of light passing through this region depends upon k, any disturbance of the particulate matter would be characterized by a change in k for that layer or for the layer of clear water just above the negative temperature gradient. This may be the case even though the mixing action was not sufficient to change the temperature profile substantially. There would be a lag in time before a return to the original state would happen.

22. SUMMARY AND CONCLUSIONS

a. Map of Tropical Atlantic Ocean

Sufficient data have been found to map the diffuse attenuation coefficient, k, of the tropical Atlantic Ocean from 15 °N latitude to 15 °S latitude. Contours spaced every 0.01 k from 0.17 to 0.04 have been drawn. The average value of k was plotted to the depth where 1% of the surface light remained. There were insufficient measurements taken to average data at each station or for each square degree as was the case for the Secchi depth maps. Thus, this map is not a statistical average over a long period of time. Nevertheless, it appears to give a good picture of the optical characteristic, k, when judged by known causes of water turbidity, such as river run-off, upwelling, deep water, and proximity to areas such as the Sargasso Sea.

b. Water Type Map of the Tropical Atlantic Ocean

An additional map showing water type has been drawn. The same basic water types were used for this map as were used for the world Secchi depth chargs prepared earliers. Water types are

described as Dirty (Turbid) Ocean Water, Coastal Water, Cool and Shelf Water, Warm Water, and Clearest Ocean Water. A legend was prepared for each water type indicating the interval of k, and the equivalent Secchi depth when using the Shannon NAVAIR-DEVCEN relationship.

c. Methods of Displaying Optical Data

Methods of displaying diffuse attenuation coefficient data for a water column have been examined and reported on. It appears that the historical method of plotting percentage surface light against depth in meters on semi-log paper presents the optical information most adequately. The slope of the curve is the diffuse attenuation coefficient, k. When compared with the curve for a homogeneous water column of pure sea water or distilled water, the various layers of regions that represent anomalies or variations in the transparency can be easily spotted. To further understand the optical properties of the water column, the graph should be compared with the temperature profile (plot of temperature against depth). Particulate matter, both organic and inorganic, finds neutral buoyancy at the point where the temperature changes rapidly from a negative gradient to a positive gradient.

d. Horizontal Distribution

By plotting a number of stations on the same graph, a horizontal distribution of k can be seen. If the area is chosen small enough, a sufficient number of representative plots can be made that will describe the horizontal distribution of k quite well. Of importance to an ORADS system will be the horizontal

variation in the optical properties of the search area. This would be important to the dynamic range required in gain settings so as to optimize the system characteristics for the search area. The false alarm rate may be a function of the variable optical conditions.

e. Determining Water Type by an Overlay

An overlay has been prepared which indicates the k values (slopes) for the different types of water. When placed on top of the graphs described in d above, the water type can easily be determined. Of particular importance is the ability to readily see the seasonal optical changes in an area when plots have been made for different seasons of the year. From the sample plots already made, it appears that an area as large as 400 square degrees can be described in this manner.

f. Expendable Irradiance Meter

The practicability of an expendable irradiance meter is being explored. This function would either be added to the present XBT now in use or would be designed to measure only the diffuse attenuation coefficient of the water column. Irradiance measurements would be taken to depths of about 100 meters. In-water tests are presently being made by a thesis student who, at this time, is using the weight, canister, and wire of a standard XBT. This technique has potential for obtaining a more accurate irradiance measurement than cable lowered meters which are subject to ship and current movements.

g. Sensing perturbations of turbid water with ORADS

The data mapped by Jung for certain coastal areas and the western Mediterranean Sea indicate that most of these coastal

waters have a shallow layer of turbid water overlaying cleaner water. This turbid water will restrict the range of an ORAD system, however, if the passage of a submarine through these waters causes perturbations that are detectable with an ORAD system, then its usefulness would be increased measurably. For this reason, it is important that the causes and characteristics of turbid waters be studied. These studies should include determining where these turbid waters are, the depth of the layer, its horizontal extent, seasonal and diurnal variations, river run-off, prevailing winds that carry dust from the continents, water temperature, upwellings, and other conditions that determine the extent, magnitude, and variations of water turbidity.

h. Measuring optical characteristics from spectral radiance of oceans

Another technique that may be used for obtaining the optical properties of the water column by measuring the spectral radiance from above the surface has been described. This method promises to obtain an average optical characteristic without the necessity for taking many point by point measurements. In order to obtain a reasonably accurate evaluation, some ground truth data are necessary. It may be that after the average characteristics have been determined by the more conventional methods, this new technique could be used to establish the seasonal changes. Radiative transfer theory is now being developed to make the technique viable.

i. Relationship between ORADS range and optical properties of water

In order to make maximum use of these different kinds of data, and to operate the ORAD system in an optimum manner, the

relationships between the system and the optical parameters, k, Z_s, and α must be determined. The interpretation of the display of the ORADS will greatly depend upon a knowledge of the optical properties of the search area. As has been pointed out, the design parameters of the system will also depend upon these optical properties. If the relationships can be found, then the ORAD system would become a very useful tool for measuring the optical properties. When mounted in an aircraft, the optical properties of large ocean areas could be measured rapidly.

j. Program for obtaining optical characteristics of the ocean

It has been concluded that there are not enough k data available to contour all of the world's oceans and seas. There are data available for many of the coastal areas, areas where there is apt to be high fishing potential, and in some channels, bays, and small seas. Some of these regions are of strategic concern to the Navy. The data are of mixed type, some being Secchi depth data, and some taken with an α meter or k meter. It is very important that the interrelationships between these different types of data be found and that a program be instituted that will obtain the necessary measurements in a uniform manner. At least k and Secchi depth data should be taken simultaneously wherever possible. This will hasten the time when satisfactory relationships between these data are found.

k. The Prediction of the Characteristics of k with depth from the temperature profile.

Preliminary comparison of k and temperature with depth indicates that it may be possible to predict the characteristics of the diffuse attenuation coefficient of the water column by

knowing the temperature profile. Absolute values of k may not be possible to predict, however the depth at which abrupt changes in k take place, and whether the change will be large or small, seems within the realm of possibility to predict. A simultaneous measurement of temperature and light intensity or k with depth would be valuable if it can be shown that disturbances in the water column modify k and are detectable with an ORIC system. Such information may be valuable in the prediction of false targets and for estimating the noise characteristics of the water column being probed.

APPENDIX A

The purpose of this study was to review what had been done in the past and where modern technology stood concerning the measurement of optical properties of sea water. A very careful search was made to insure that data used was not Secchi depth data that had been translated into k data through the use of the Poole-Atkins relationship or some similar equation. One of the objectives of the study was to see how much irradiance meter data could be gathered which when contoured would result in a k atlas for a substantial body of water. When compared with the abundance of Secchi depth data, true irradiance data is rather scarce. Only one cruise (Pillsbury, University of Miami Oceanographic Vessel) indicated the kind of meter used. That meter was a Marine Advisor Irradiance Meter, Model C-1A. All other cruises simply indicated that a marine photometer was used. The data was further scrutinized to see if it fit the pattern of the Poole-Atkins equation. If it did, it was considered suspect and not used. No mention was made how the various photometers were calibrated, the wavelength, or bandwidth.

The specifications for the Marine Advisor Irradiance Meter, Model C-1, are given below. It is hoped that the other photometers had similar specifications.

a. The sensors are supplied with flat-plate photovoltaic cells in conformance with the cosine law.

b. The underwater sensor is equipped with a Wratten No. 102 optical filter to match the photosensor response to the

to the response of the human eye when visibility calculations are necessary. This would not of course be desirable and would hopefully be replaced by one of the following filters: Wratten 44 for blue oceanic water (high transparency), or Wratten 60 for green coastal water (turbid water).

c. Linearity without temperature compensation is ±3%.

d. The irradiance meter indicates the depth in meters of the sensor, the ratio of surface irradiance to underwater irradiance, and the natural log of the inverse of this ratio per meter depth, which is k.

From the EQUALANT data it is not possible to state for certain that any of the irradiance meters had similar specifications with the exception of the Pillsbury cruise. Many of the vessels taking part in the data collection effort were from other nations. EQUALANT instructions did, however, attempt to set the general rules for data collection. It appears that all optical data were taken when the sun was near the zenith, and that some uniformity was achieved by specifying the method for taking data and for making necessary calculations.

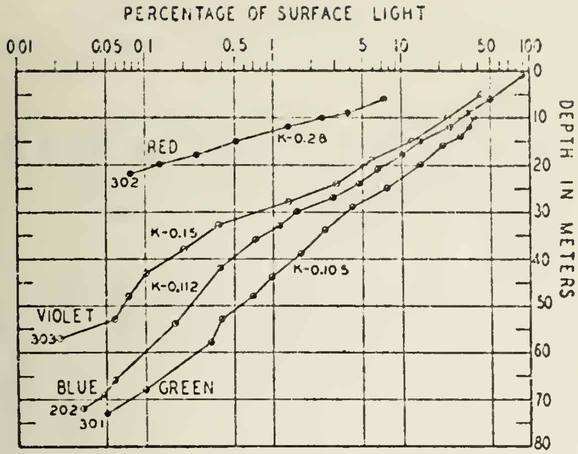


FIG. 2. Relation between depth and irradiation expressed as a percentage of the light just over the surface (logarithmic scale). Series number indicated at end of each curve. Observations made in the deep basin of the Gulf of Maine.
Series 301, 302, 303 at Station 2237. July 17, 1934,
Series 202 at Station 1722. July 15, 1933.

Fig. 1a

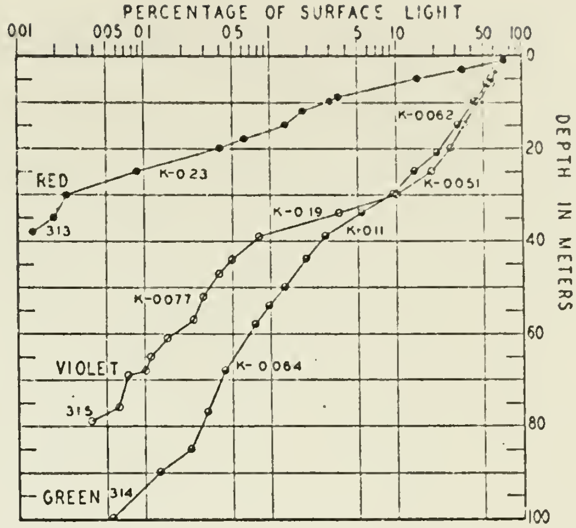


FIG. 5. Observations made in the "Slope Water" between the Gulf Stream and the Continental Shelf.
Series 313, 314 and 315 at Station 2246 on July 25, 1934.

Fig. 1c

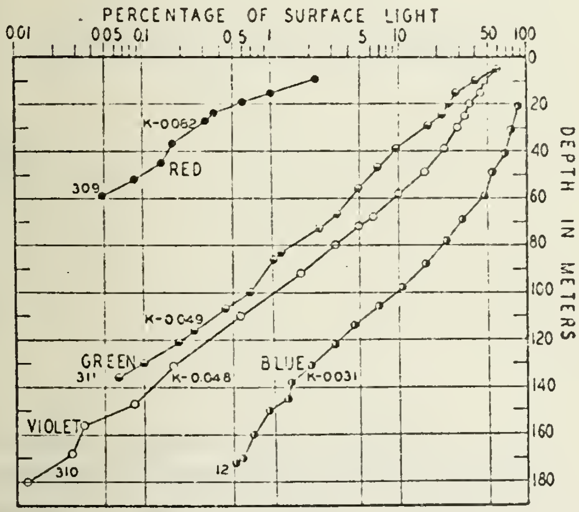


FIG. 4. Observations made in the Sargasso Sea and Gulf Stream.
Series 309 at Station 2243 on July 22, 1934,
Series 310 and 311 at Station 2245 on July 24, 1934,
Series 12 at Station 1041 on August 15, 1931.

Fig. 1b

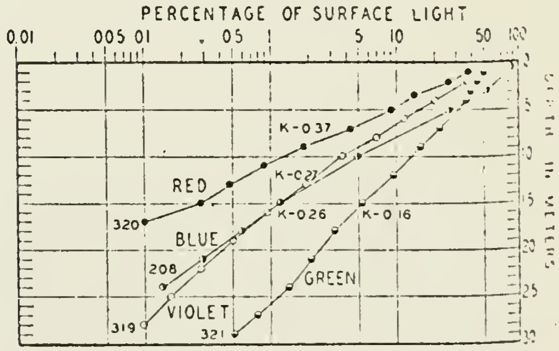


FIG. 6. Observations made off Gay Head.
Series 319, 320 and 321 on August 17, 1934,
Series 208 on September 2, 1933.

Fig. 1d

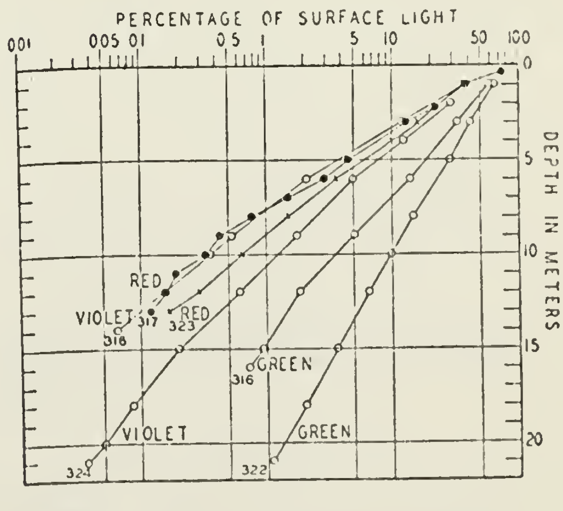


FIG. 7. Observations made in Vineyard Sound.
Series 322, 323, 324 on August 21, 1934.
Observations made in Woods Hole Harbor.
Series 316, 317, 318 on August 9, 1934.

Graphs from: R. H. Oster & G. L. Clarke
"The Penetration of Red, Green, and Violet
Components of Daylight into Atlantic Waters",
Journal of the Optical Society of America,
Volume 25, March 1953

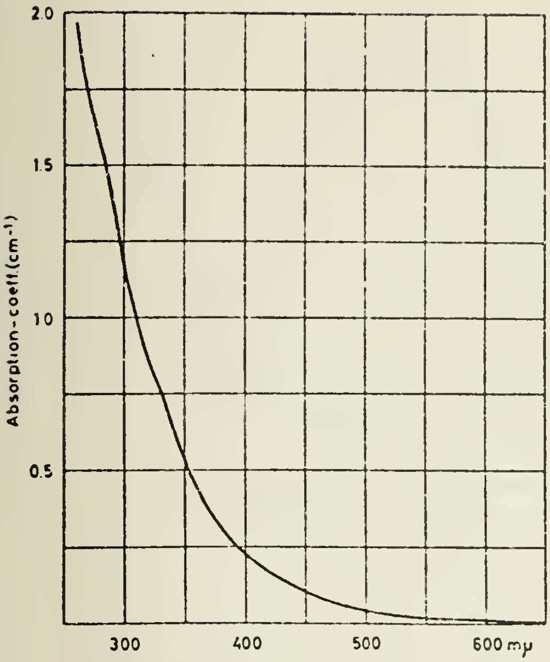


FIG. 1. Absorption curve of yellow substance.

FIG. 2a

Graphs from: N. G. Jerlov, "Optical Classification of Ocean Water", Tenth Pacific Science Congress Series, Univ. of Hawaii, <u>Physical Aspects of Light in the Sea</u>, John E. Tyler, Editor, 1961

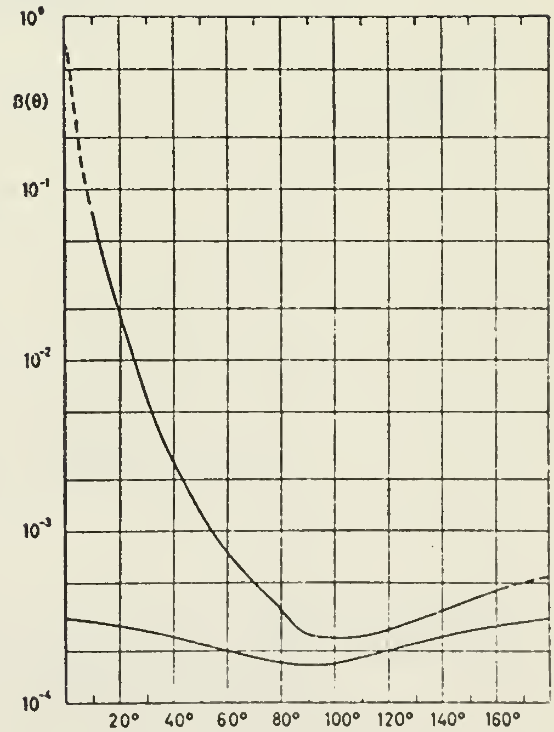


FIG. 2. Volume scattering function for ocean water (upper curve) and pure water (lower curve) for blue light (465 μ).

Fig. 2b

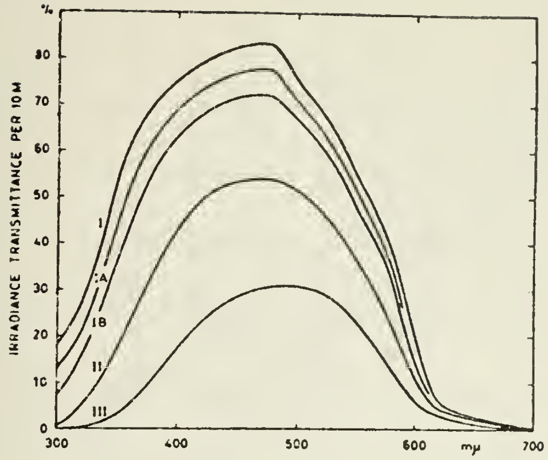


FIG. 5. Irradiance transmittance per 10 m for different types of ocean water.

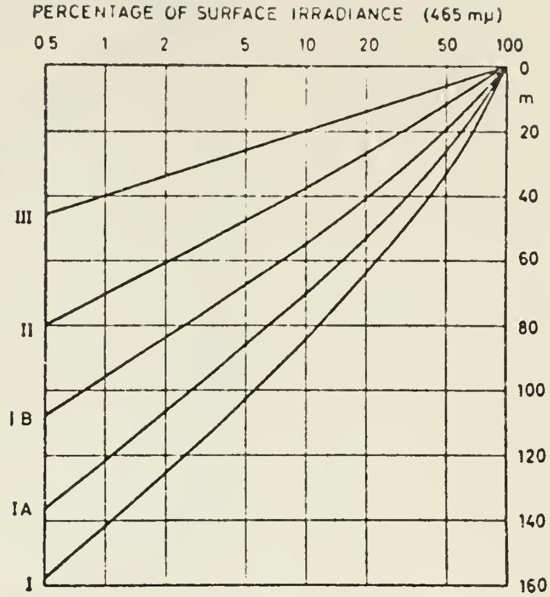


FIG. 6. Logarithmic curves of irradiance (465 μ) for different types of ocean water.

Fig. 2c

Fig. 2d

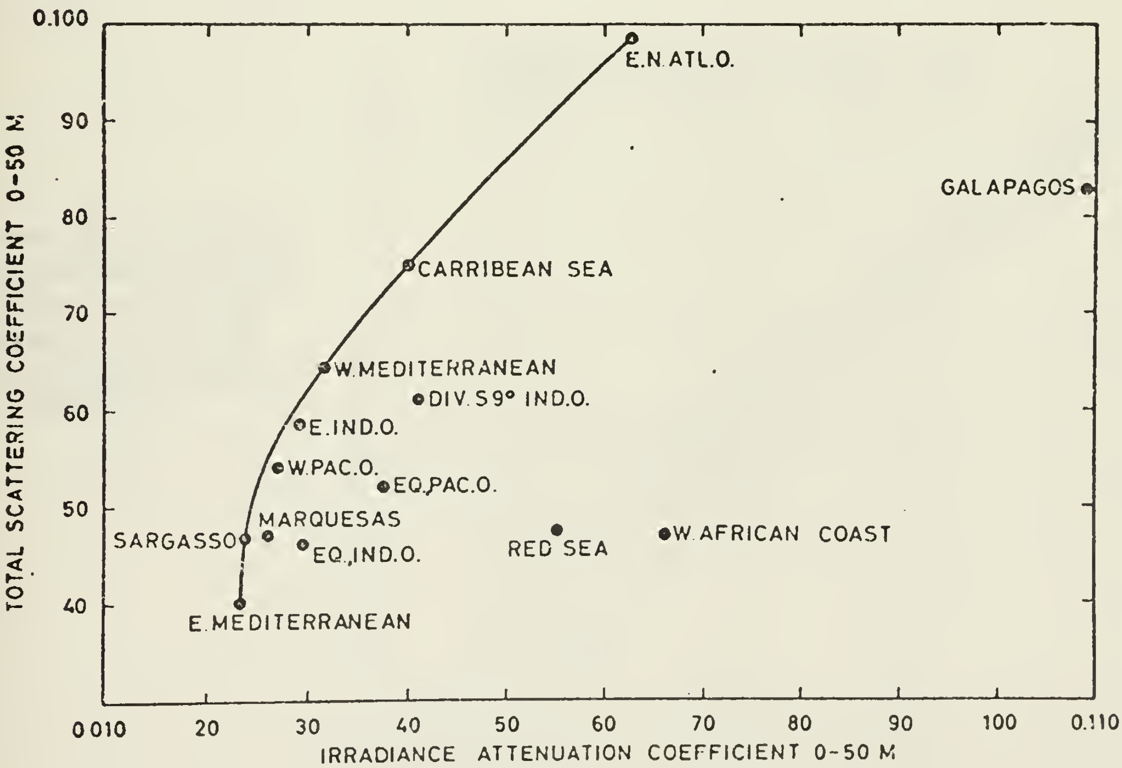


FIG. 4. Relationship between irradiance attenuation and total scattering for blue light (465μ).

Fig. 2e

Graphs from: N. G. Jerlov, "Optical Classification of Ocean Water", Tenth Pacific Science Congress Series, Univ. of Hawaii, Physical Aspects of Light in the Sea, John E. Tyler, Editor, 1961

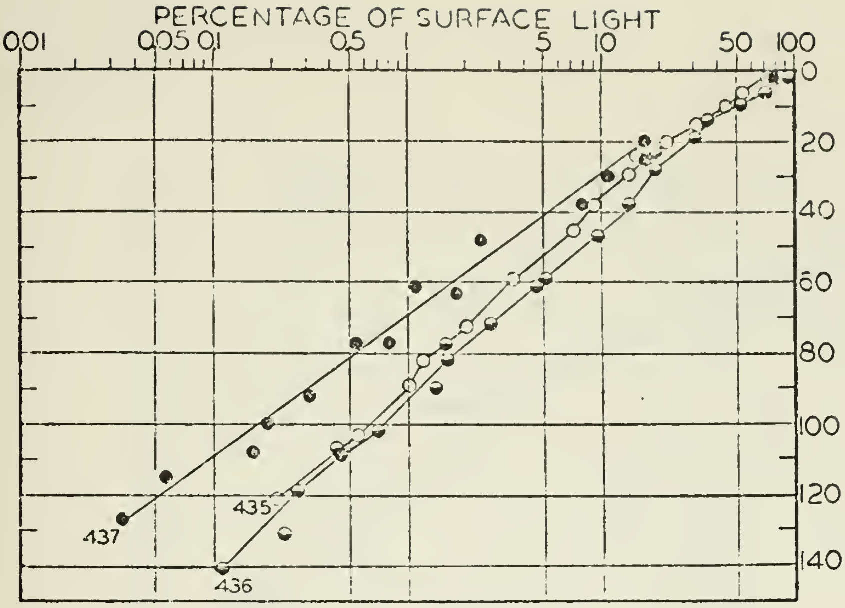


Figure 27. Relation between depth and irradiation expressed as a percentage of the light just over the surface (logarithmic scale). Series numbers indicated at end of each curve.

Series	Locality	Latitude	Longitude	Date	Time (E.S.T.)	Sky*	Sea	Wind†
435	Antilles Current	24°00′N	59°03′W	Jan. 4, 1937	09:50–10:44	bc	moderate	3–4
436	No. Equatorial Current	12°04′	60°29′	Jan. 12, 1937	10:55–11:45	o	rough	4–5
437	Caribbean Sea	15°20′	67°10′	Jan. 26, 1937	10:00–10:42	bc	moderate	4–5

* U. S. Weather Bureau symbols. † Wind force on Beaufort Scale.

Fig. 3a

Graphs from: G. L. Clarke, "Light Penetration in the Caribbean Sea and in the Gulf of Mexico", Journal of Marine Research, Volume 1, No. 2, 1937-38.

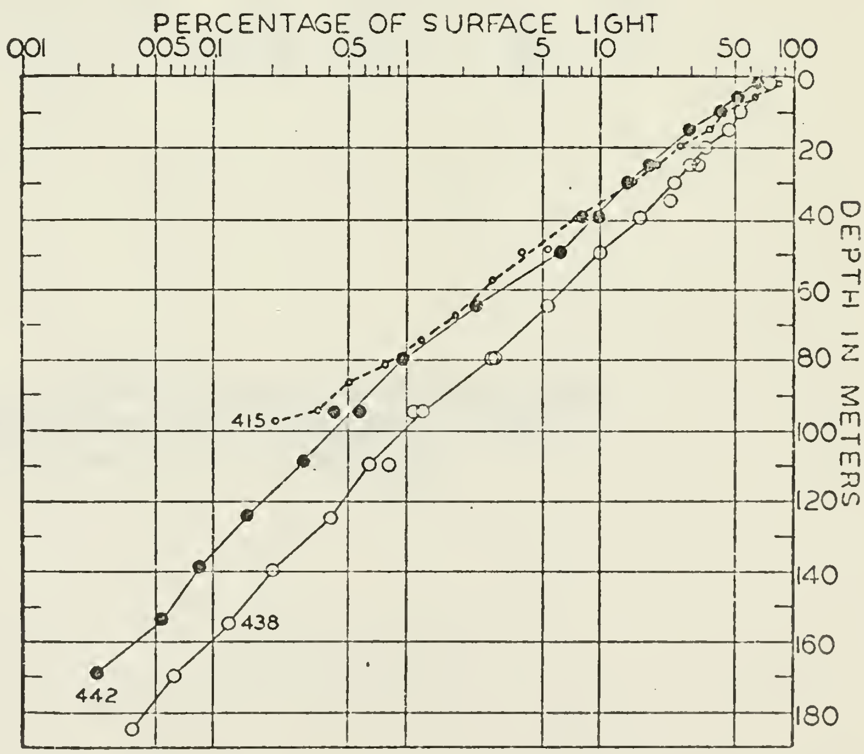


Figure 28. Relation between depth and irradiation expressed as a percentage of the light just over the surface.

Series	Locality	Latitude	Longitude	Date	Time	Sky	Sea	Wind
415	Gulf Stream (S of Grand Banks)	39°56′N	48°40′W	Sept. 15, 1935	15:35–17:00 (L.A.T.)	o	slight	3–4
438	Cayman Sea	18°38′	79°12′	Feb. 28, 1937	10:45–12:42 (E.S.T.)	bc	smooth	1
442	Gulf of Mexico	29°14′	87°48.5′	April 11, 1937	10:30–11:18 (C.S.T.)	b	smooth	1

Fig. 3b

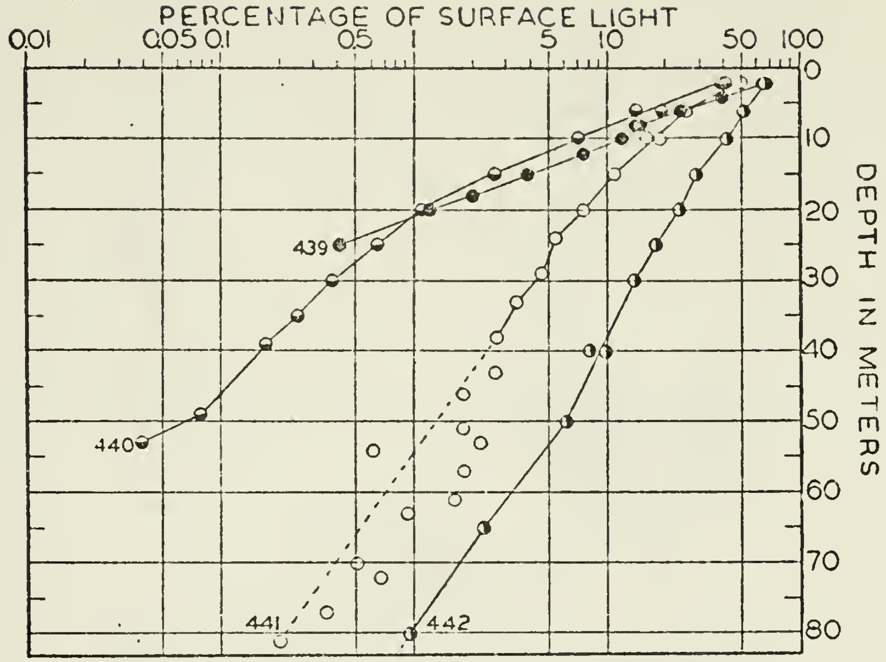


Figure 29. Relation between depth and irradiation expressed as a percentage of the light just over the surface.

Series	Locality	Latitude	Longitude	Date	Time (C.S.T.)	Sky	Sea	Wind
439	Gulf of Mexico	29°27′N	88°48′W	April 9, 1937	11:34–11:54	b	slight	3
440	Gulf of Mexico	29°16′	88°50′	April 9, 1937	15:30–15:53	bc	slight	3
441	Gulf of Mexico	29°08′	88°39′	April 10, 1937	10:45–11:30	b	slight	3
442	Gulf of Mexico	(See Fig. 5)						

Fig. 3c

Graph from: G. L. Clarke, "Light Penetration in the Caribbean Sea and in the Gulf of Mexico", Journal of Marine Research, Volume 1, No. 2, 1937-38.

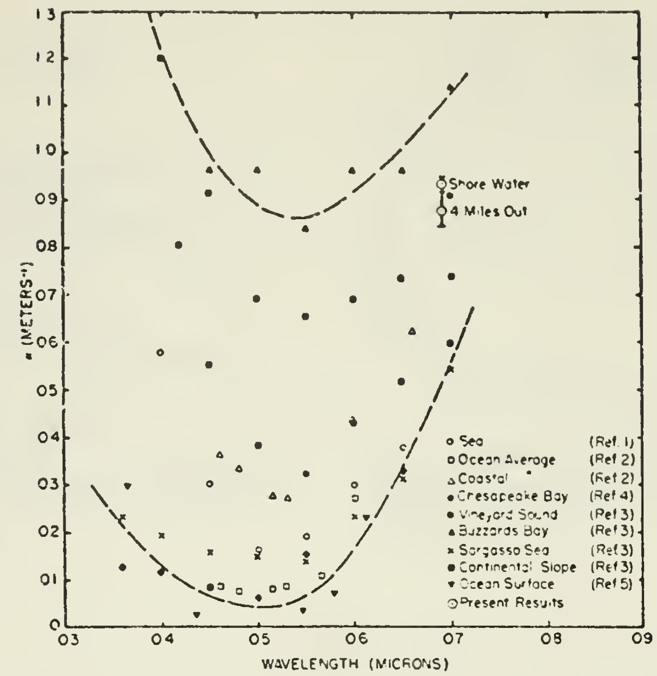


Fig. 1. Sea water attenuation coefficient κ as a function of wavelength in the visible. Present results shown by the dotted circles were measured with a ruby laser (0.6943 μ). Dashed curves give approximate upper and lower limits of κ.

Fig. 4a

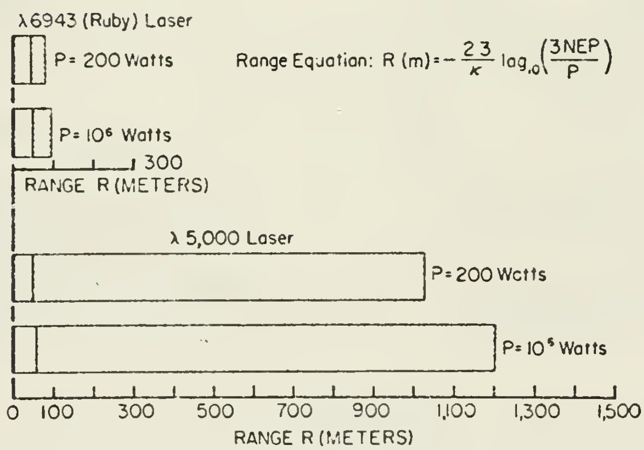


Fig. 2. Calculated underwater range limits for ruby and hypothetical blue-green lasers. The longer and shorter bars indicate maximum and minimum ranges calculated using the extreme values of κ shown by the dashed lines in Fig. 1.

Fig. 4b

Graphs from: J. P. Mutschlecner, D. K. Burge, & E. Regelson, "Sea Water Attenuation Measurements with a Ruby Laser, Applied Optics, Vol. 2, No. 11, November 1963, Page 1202

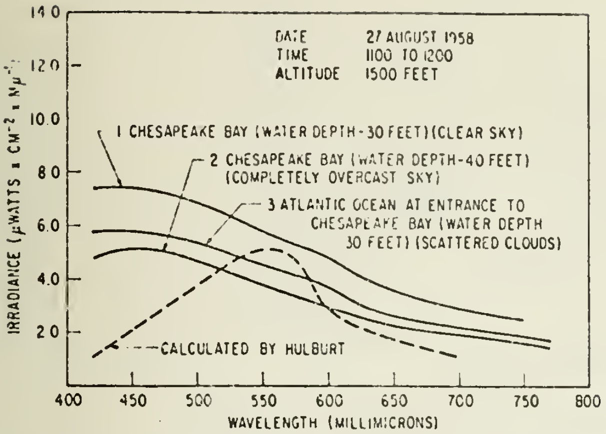


Fig. 5. Typical absolute spectral-irradiance curves of upwelling light over the Chesapeake Bay and the Atlantic Ocean at the entrance to the Bay.

ig. 5a

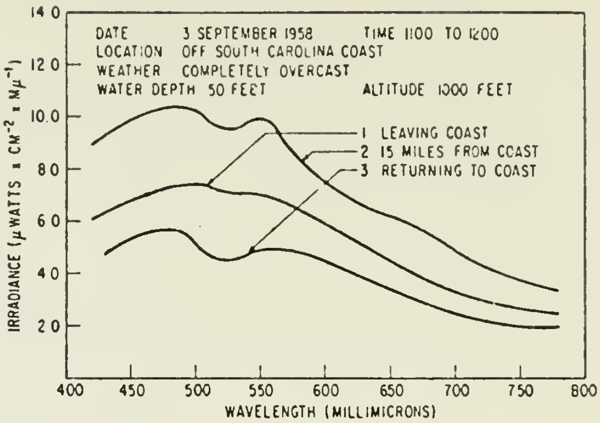


Fig. 7. Typical absolute spectral-irradiance curves of upwelling light over the North Atlantic Ocean approximately 15 miles off the South Carolina Coast between Charleston, South Carolina and Savannah, Georgia.

Fig. 5c

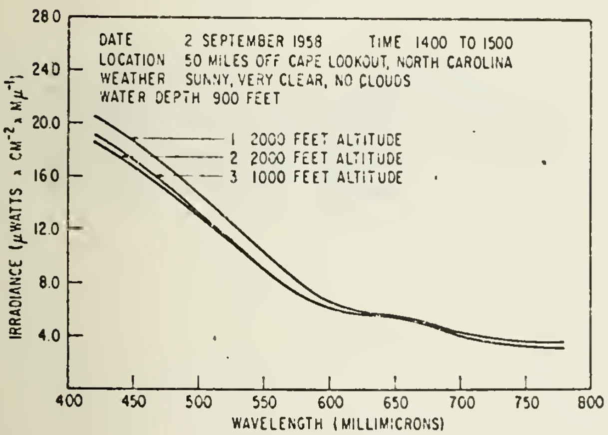


Fig. 6. Typical absolute spectral-irradiance curves of upwelling light over the North Atlantic Ocean approximately 50 miles off Cape Lookout, North Carolina.

ig. 5b

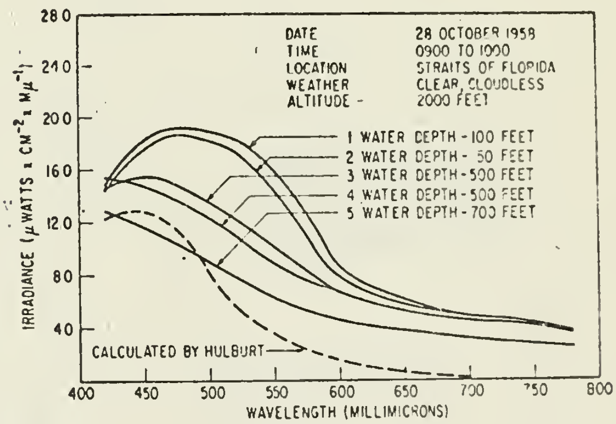


Fig. 8. Typical absolute spectral-irradiance curves of upwelling light over the Straits of Florida.

Fig. 5d

raphs from: G. L. Stamm, R. A. Langel, "Some Spectral Irradiance Measurements f Upwelling Natural Light off the East Coast of the United States", Journal f the Optical Society of America, Volume 51, No. 10, October 1961.

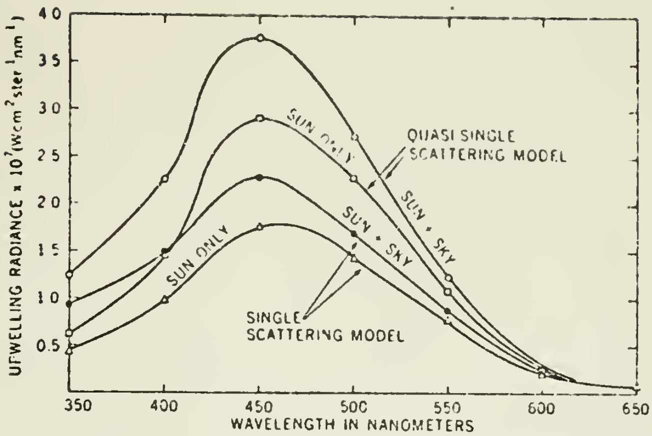


Fig. 8. Upwelling radiance spectrum predicted for the Sargasso Sea using two optical models of the sea.

Fig. 6a

Graphs from: W. R. McCluney "Ocean Color Spectrum Calculations", Applied Optics, Vol. 13, No. 10, October 1974.

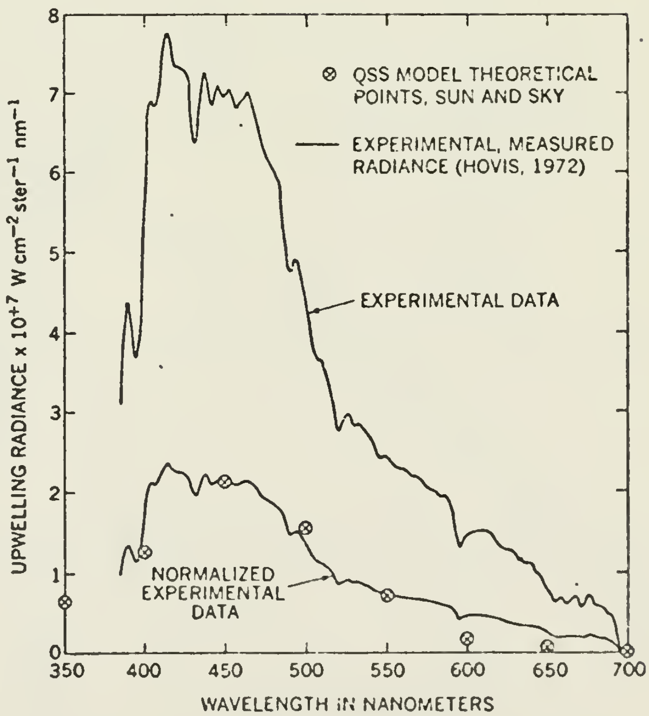


Fig. 9. Comparison of theoretical upwelling radiance spectrum for the Sargasso Sea with measurements made by Hovis at an altitude of 305 m, 250 km NE of Cape Hatteras in 1972.

Fig. 6b

DIFFUSE ATTENUATION COEFFICIENT, k (m^{-1})
FOR TROPICAL ATLANTIC WATERS

FIG. 7

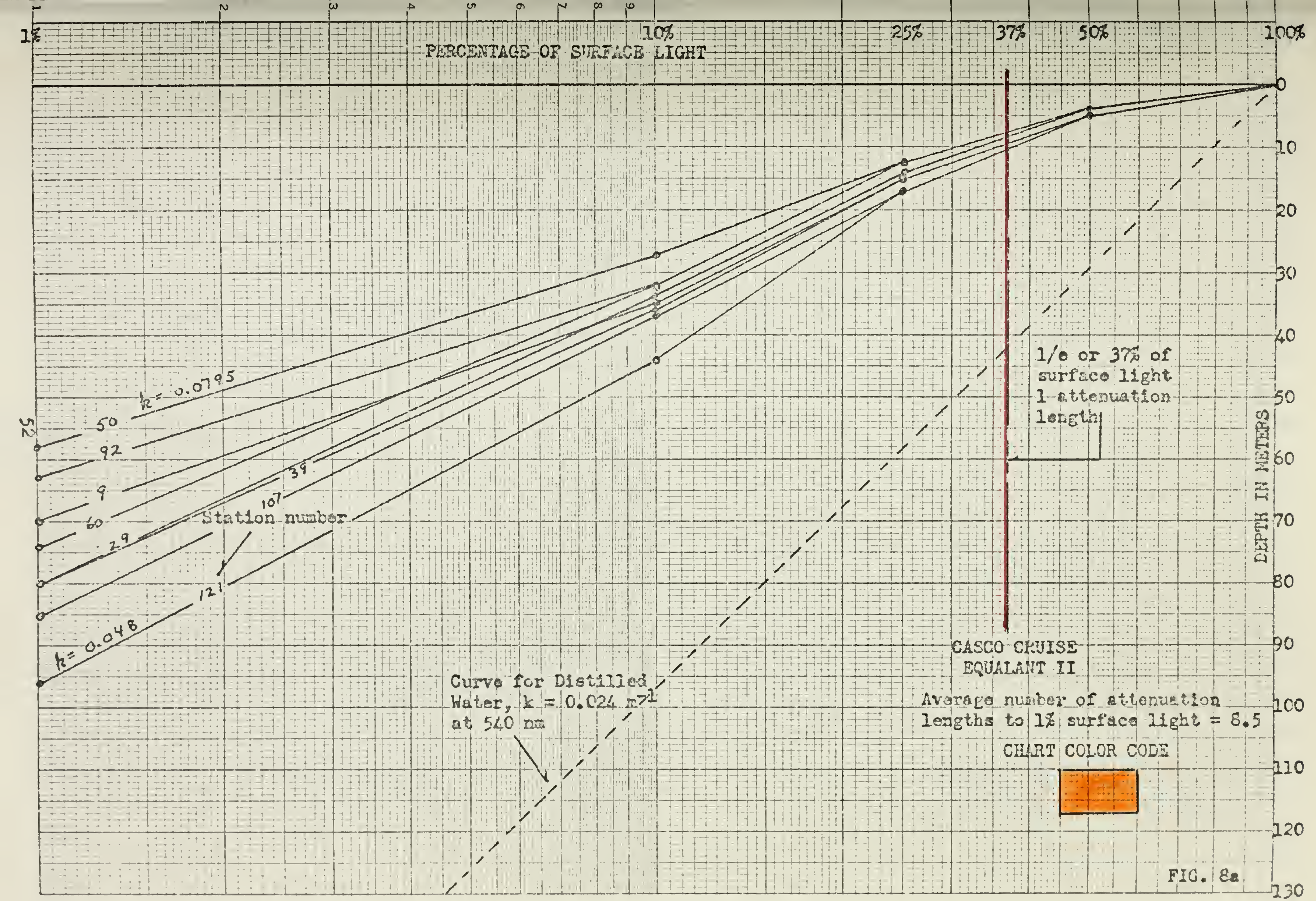
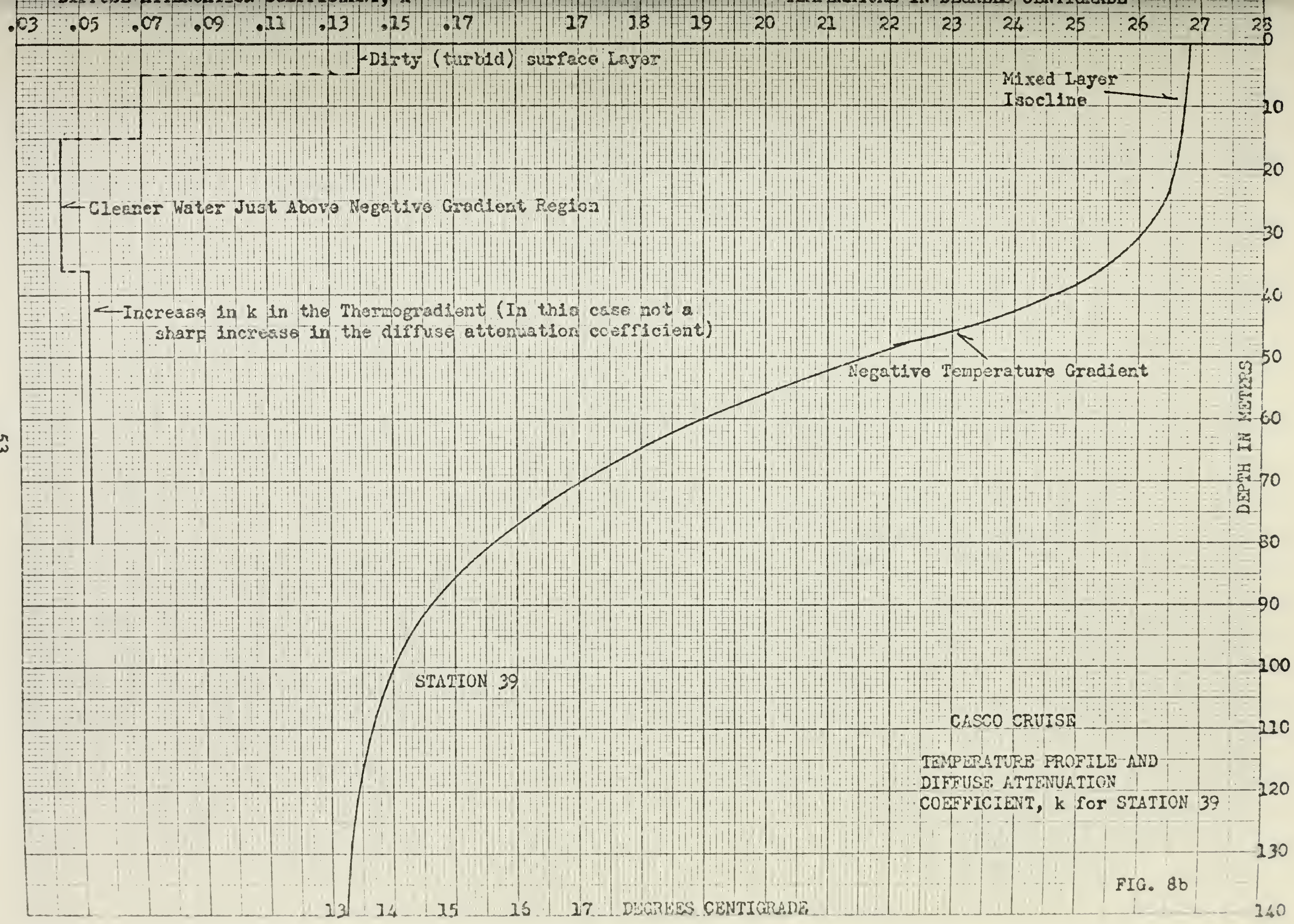

PERCENTAGE OF SURFACE LIGHT
1%
10%
25%
37%
50%
100%
DEPTH IN METERS
0
10
20
30
40
50
60
70
80
90
100
110
120
130
1/e or 37% of
surface light
1 attenuation
length
$k = 0.0795$
50
92
9
60
29
39
107
Station number
121
$k = 0.048$
Curve for Distilled
Water, $k = 0.024\ m^{-1}$
at 540 nm
CASCO CRUISE
EQUALANT II
Average number of attenuation
lengths to 1% surface light = 8.5
CHART COLOR CODE

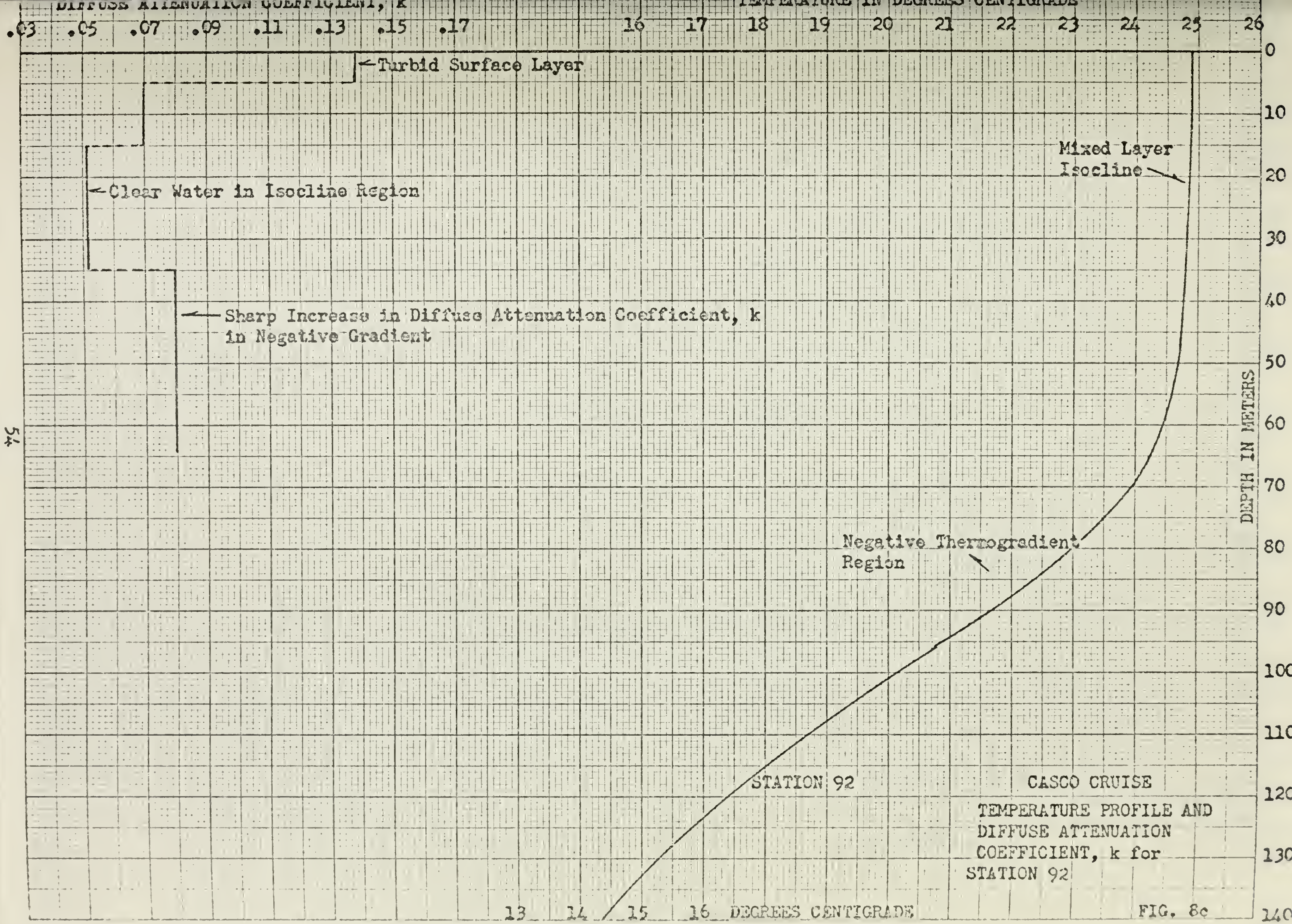
FIG. 8a



CASCO CRUISE

TEMPERATURE PROFILE AND DIFFUSE ATTENUATION COEFFICIENT, k for STATION 39

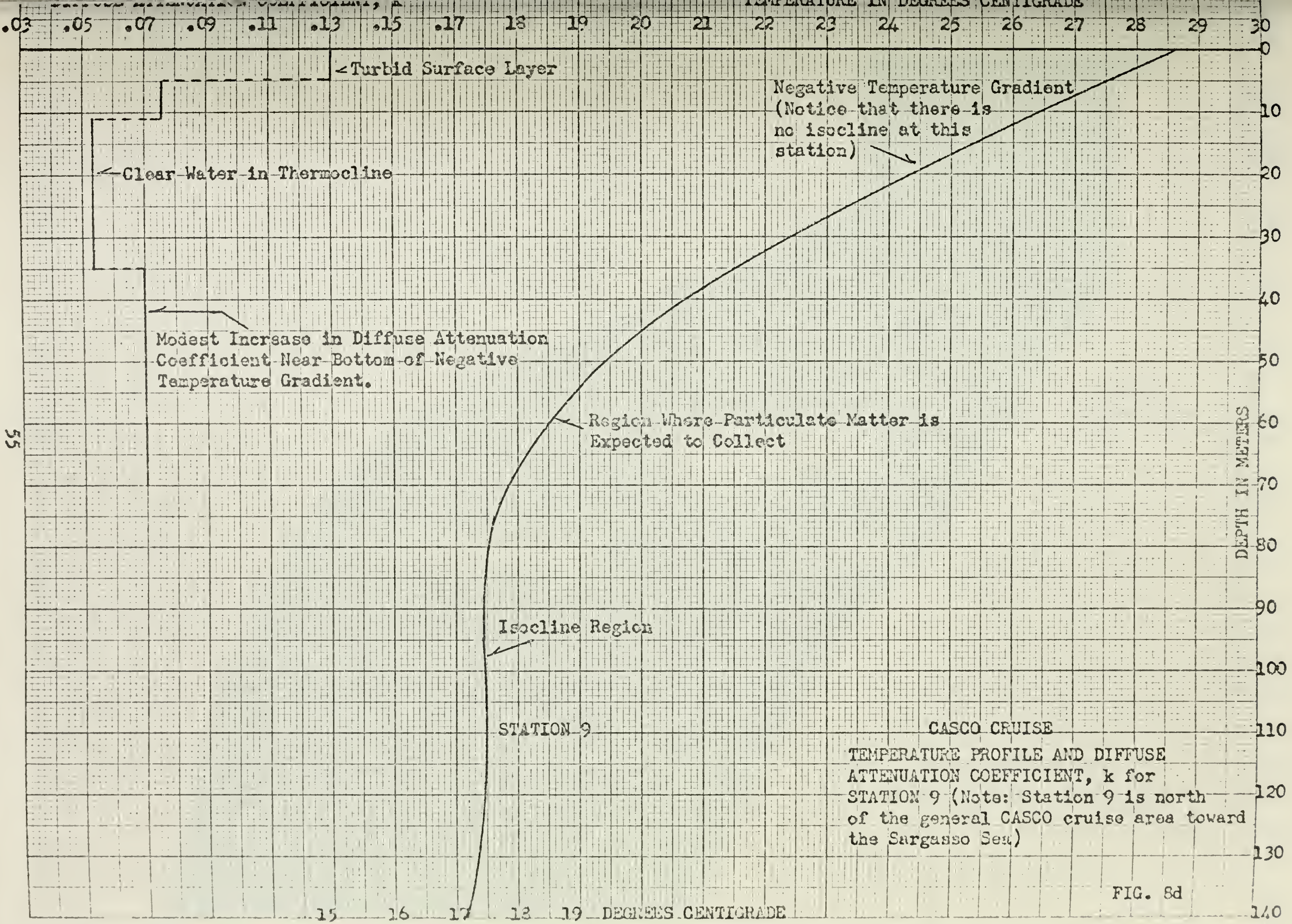
FIG. 8b



CASCO CRUISE

TEMPERATURE PROFILE AND DIFFUSE ATTENUATION COEFFICIENT, k for STATION 92

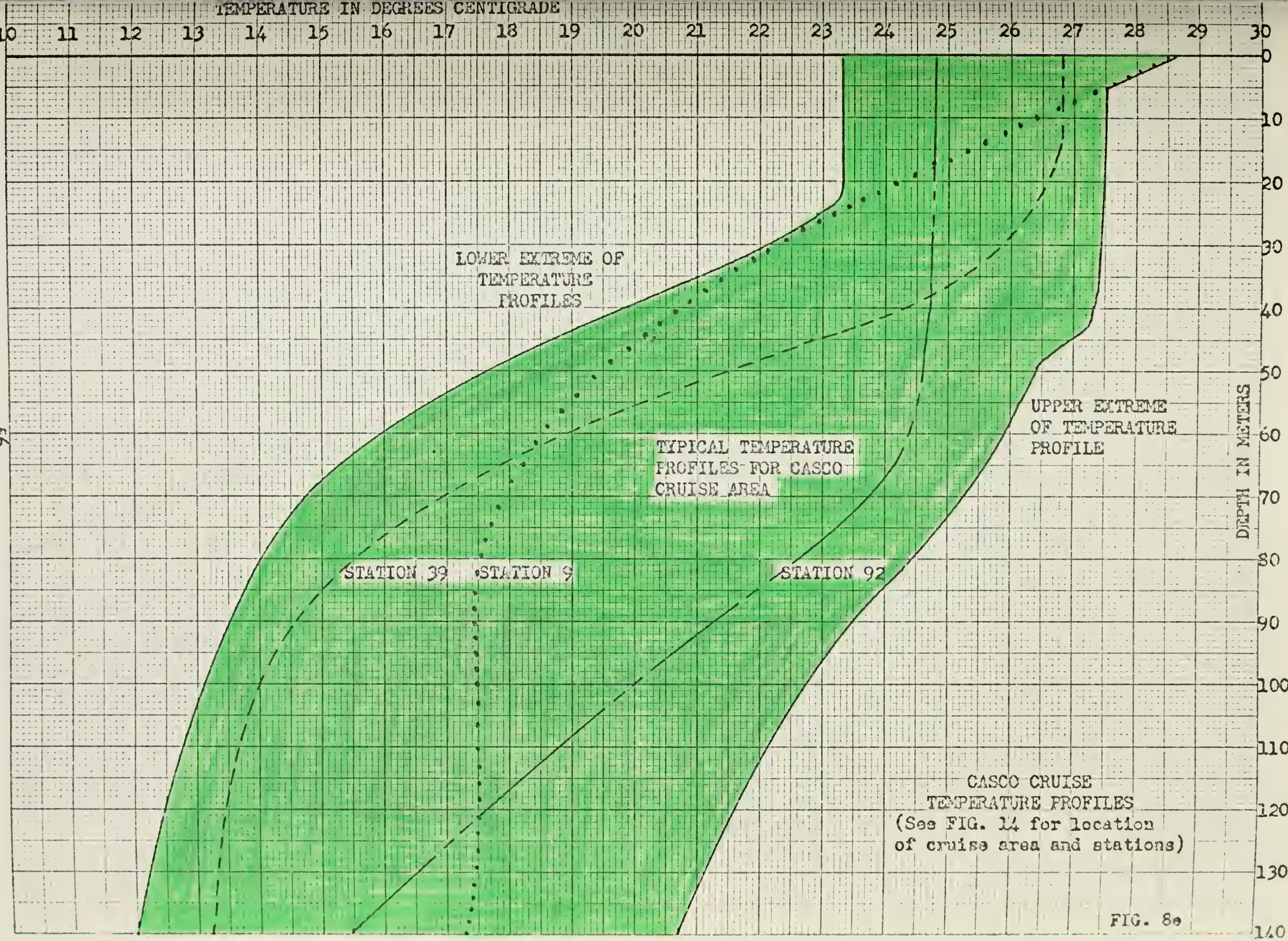
FIG. 8c



CASCO CRUISE

TEMPERATURE PROFILE AND DIFFUSE ATTENUATION COEFFICIENT, k for STATION 9 (Note: Station 9 is north of the general CASCO cruise area toward the Sargasso Sea)

FIG. 8d



CASCO CRUISE TEMPERATURE PROFILES
(See FIG. 14 for location of cruise area and stations)

FIG. 8e

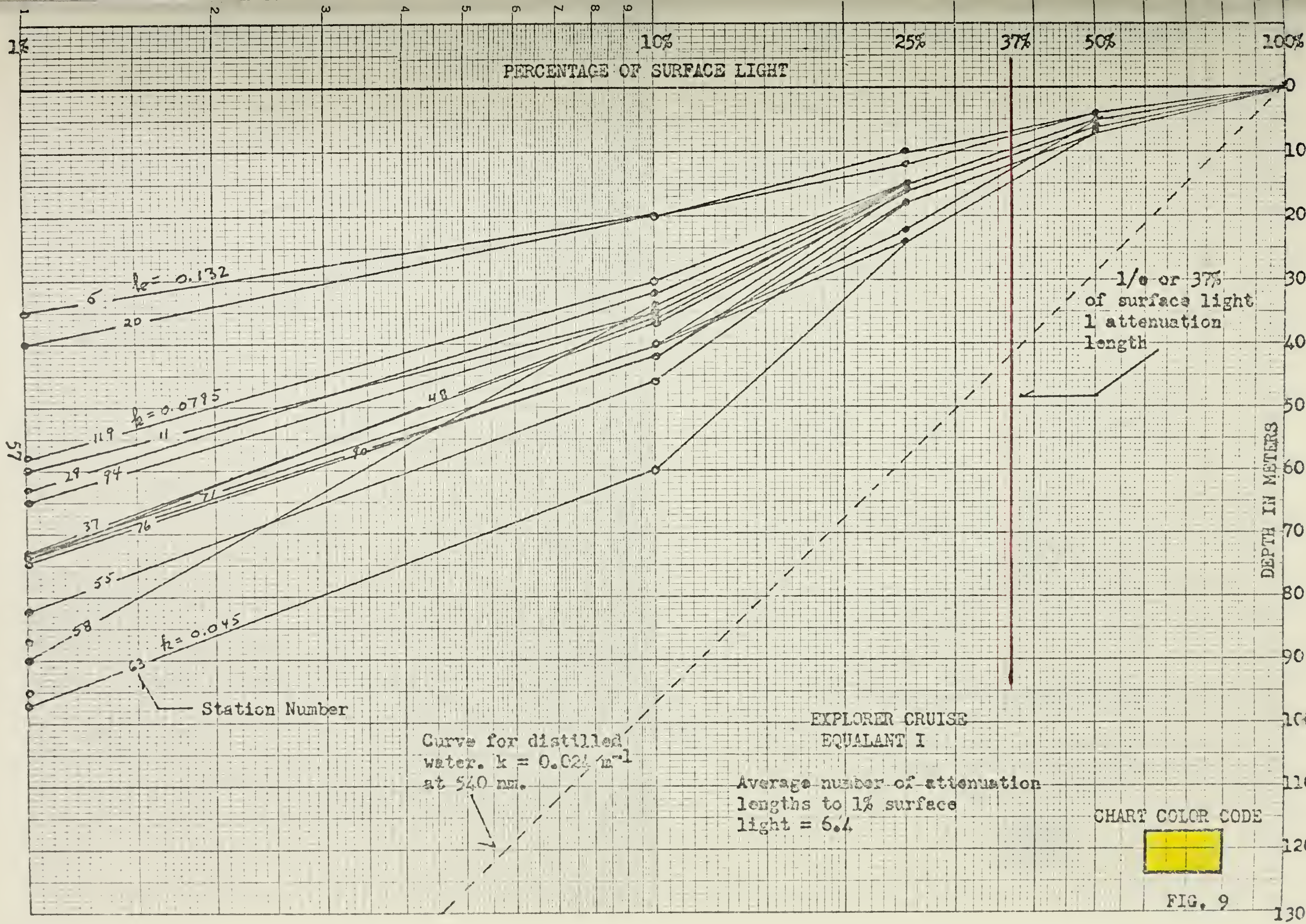

PERCENTAGE OF SURFACE LIGHT
1%
10%
25%
37%
50%
100%
DEPTH IN METERS
k = 0.132
k = 0.0795
k = 0.045
Station Number
1/e or 37% of surface light 1 attenuation length
Curve for distilled water. k = 0.024 m⁻¹ at 540 nm.
EXPLORER CRUISE
EQUALANT I
Average number of attenuation lengths to 1% surface light = 6.4
CHART COLOR CODE

FIG. 9

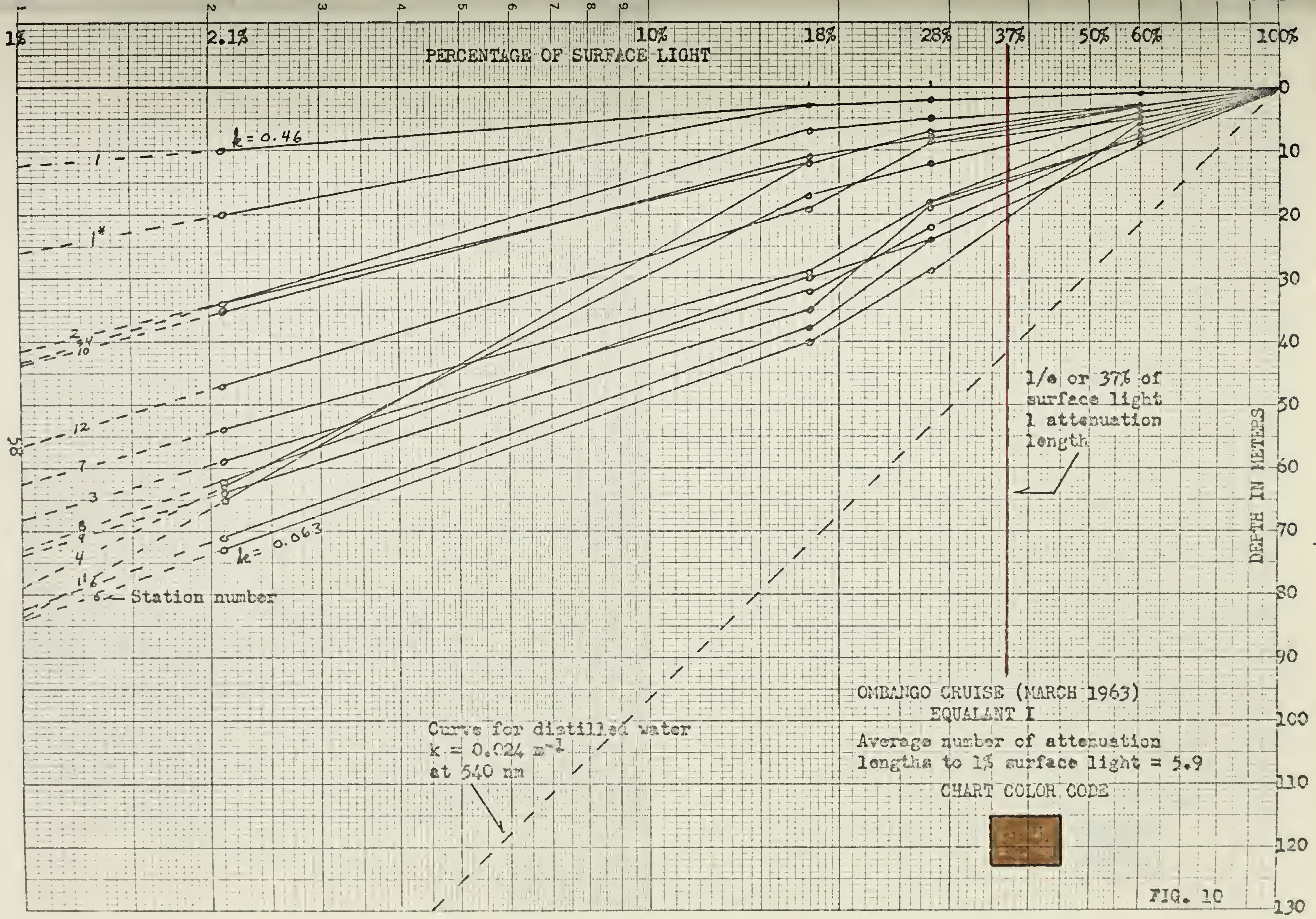
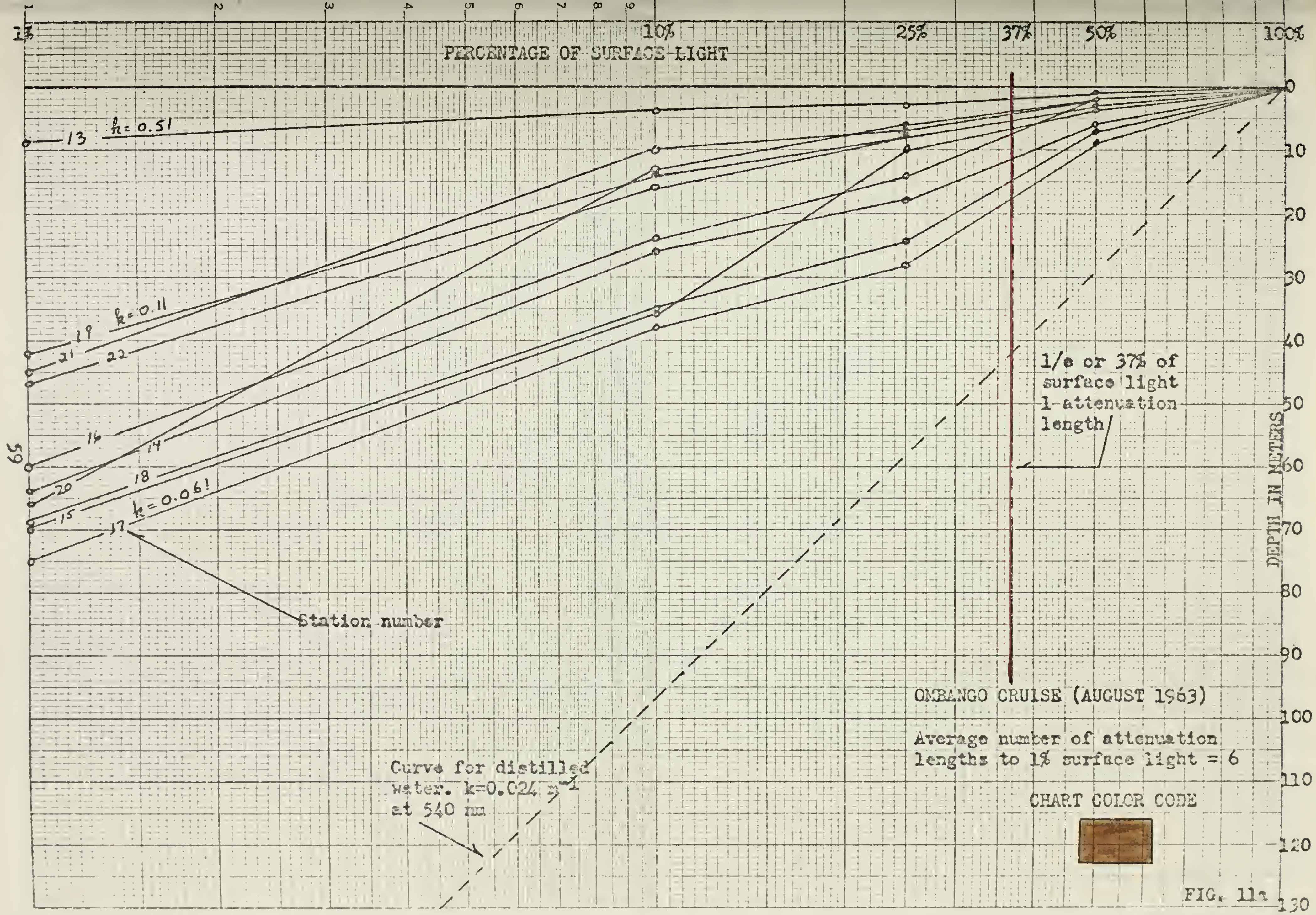
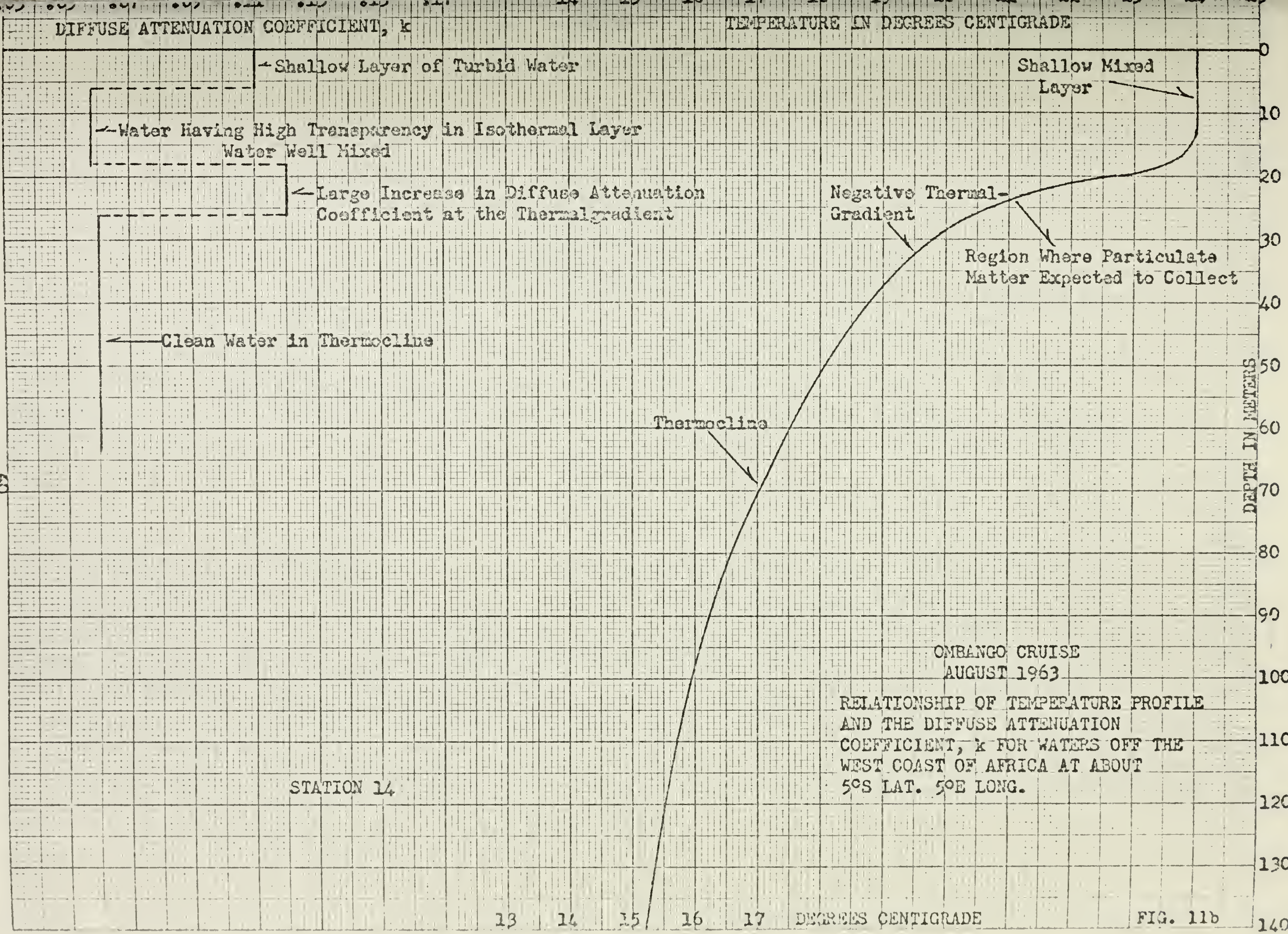

PERCENTAGE OF SURFACE LIGHT
1%
2.1%
10%
18%
28%
37%
50%
60%
100%
DEPTH IN METERS
k = 0.46
k = 0.063
Station number
1/e or 37% of
surface light
1 attenuation
length
Curves for distilled water
k = 0.024 m⁻¹
at 540 nm
OMBANGO CRUISE (MARCH 1963)
EQUALANT I
Average number of attenuation
lengths to 1% surface light = 5.9
CHART COLOR CODE

FIG. 10



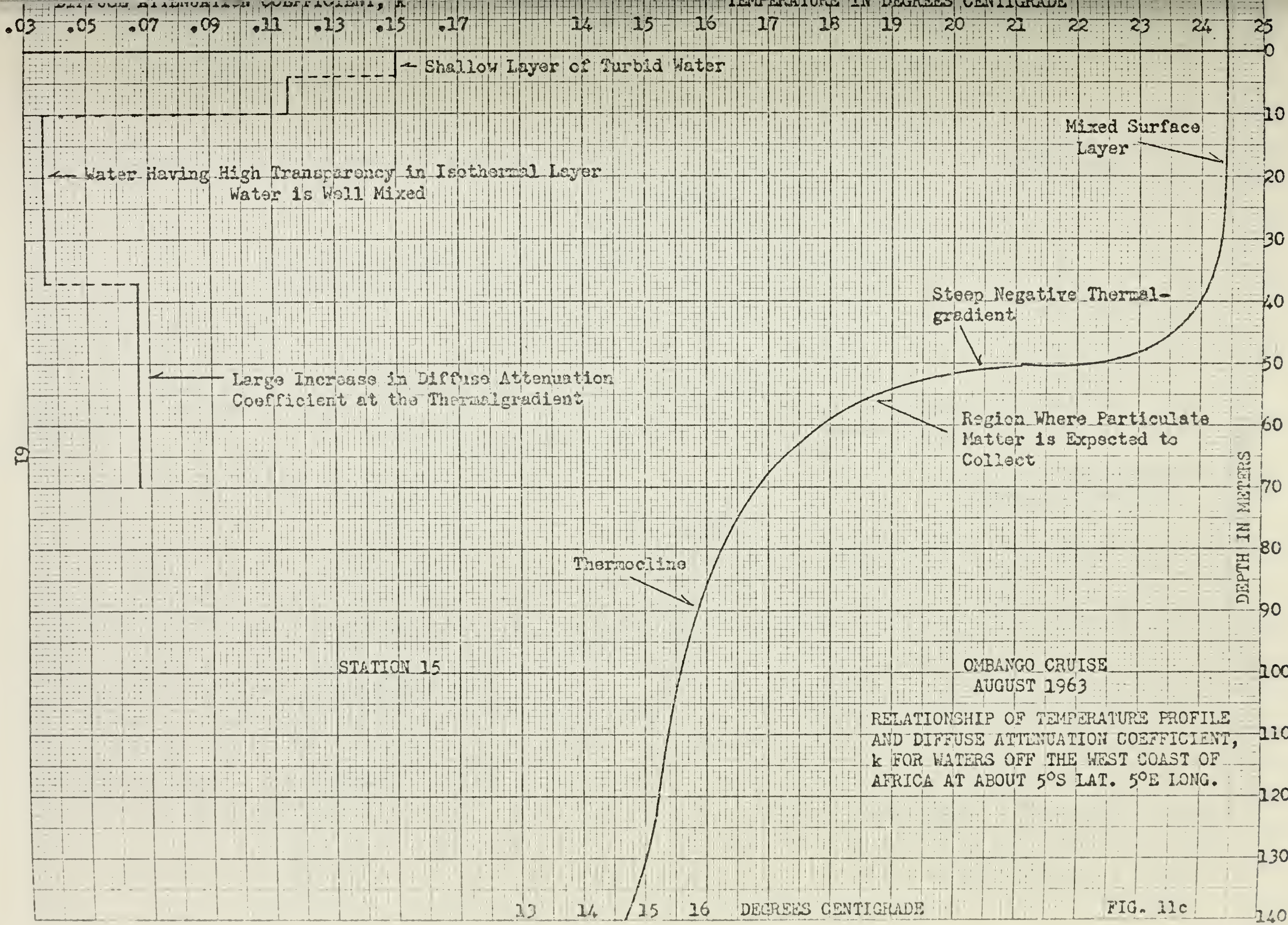
PERCENTAGE OF SURFACE LIGHT
1%
2
3
4
5
6
7
8
9
10%
25%
37%
50%
100%
DEPTH IN METERS
0
10
20
30
40
50
60
70
80
90
100
110
120
130
k=0.51
13
k=0.11
19
21
22
16
14
20
18
15
k=0.061
17
Station number
1/e or 37% of
surface light
1-attenuation
length
Curve for distilled
water. k=0.024 m-1
at 540 nm
OMBANGO CRUISE (AUGUST 1963)
Average number of attenuation
lengths to 1% surface light = 6
CHART COLOR CODE

FIG. 11a



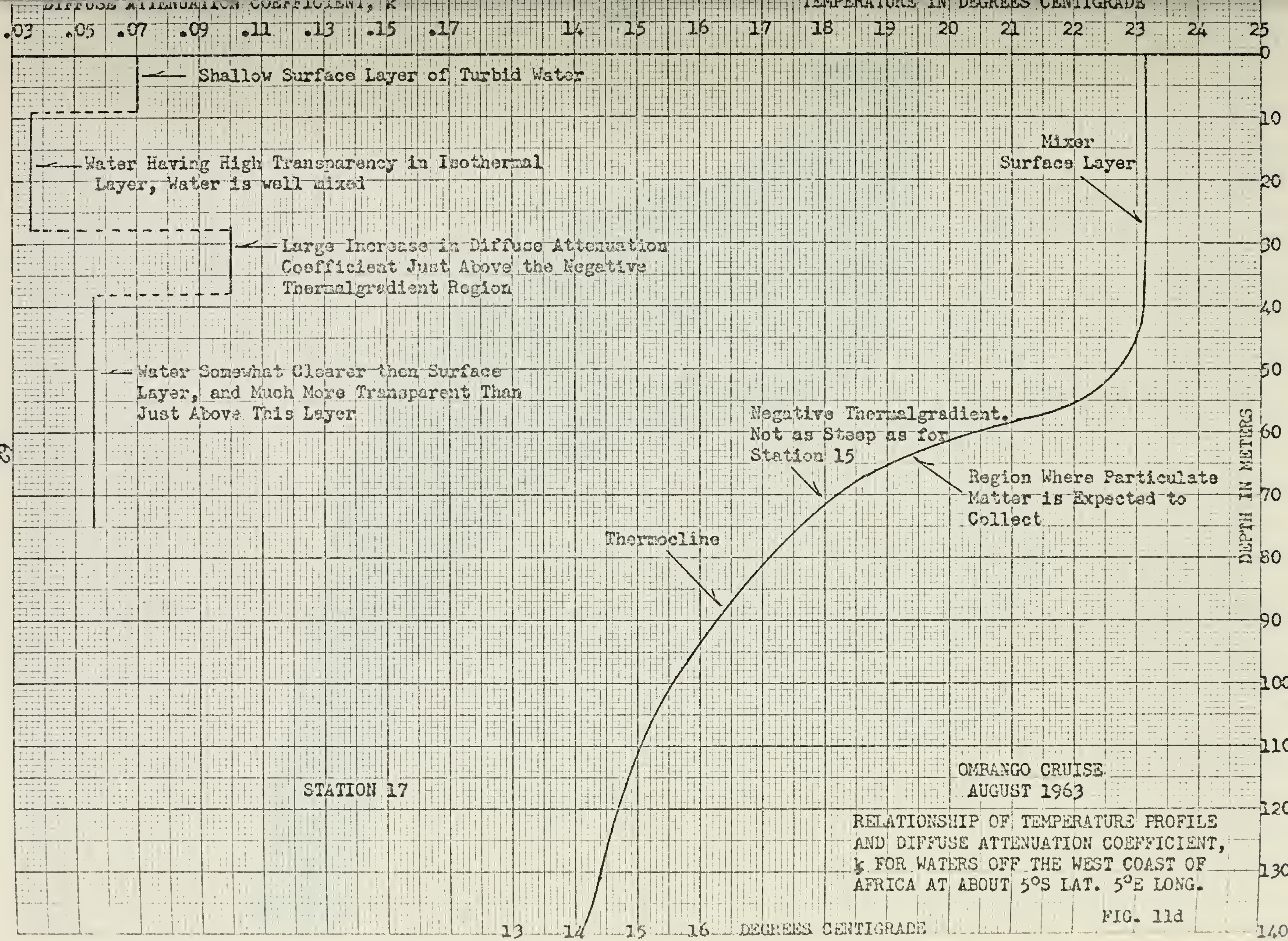
RELATIONSHIP OF TEMPERATURE PROFILE AND THE DIFFUSE ATTENUATION COEFFICIENT, k FOR WATERS OFF THE WEST COAST OF AFRICA AT ABOUT 5°S LAT. 5°E LONG.

FIG. 11b



RELATIONSHIP OF TEMPERATURE PROFILE AND DIFFUSE ATTENUATION COEFFICIENT, k FOR WATERS OFF THE WEST COAST OF AFRICA AT ABOUT 5°S LAT. 5°E LONG.

FIG. 11c



RELATIONSHIP OF TEMPERATURE PROFILE AND DIFFUSE ATTENUATION COEFFICIENT, k FOR WATERS OFF THE WEST COAST OF AFRICA AT ABOUT 5°S LAT. 5°E LONG.

FIG. 11d

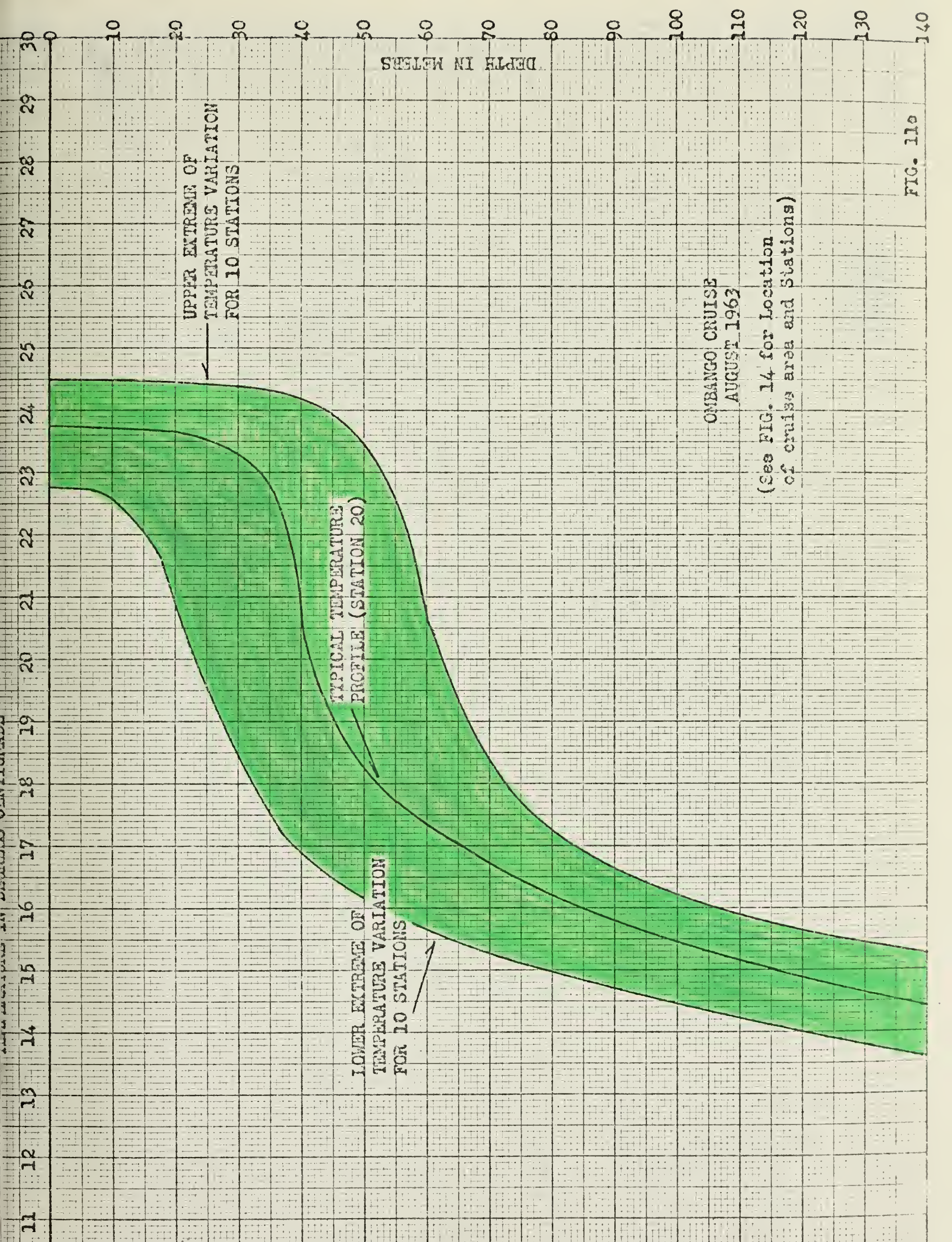

DEPTH IN METERS
UPPER EXTREME OF TEMPERATURE VARIATION FOR 10 STATIONS
TYPICAL TEMPERATURE PROFILE (STATION 20)
LOWER EXTREME OF TEMPERATURE VARIATION FOR 10 STATIONS
OMBANGO CRUISE AUGUST 1963
(See FIG. 14 for Location of cruise area and Stations)
10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30
0 10 20 30 40 50 60 70 80 90 100 110 120 130 140

FIG. 11c

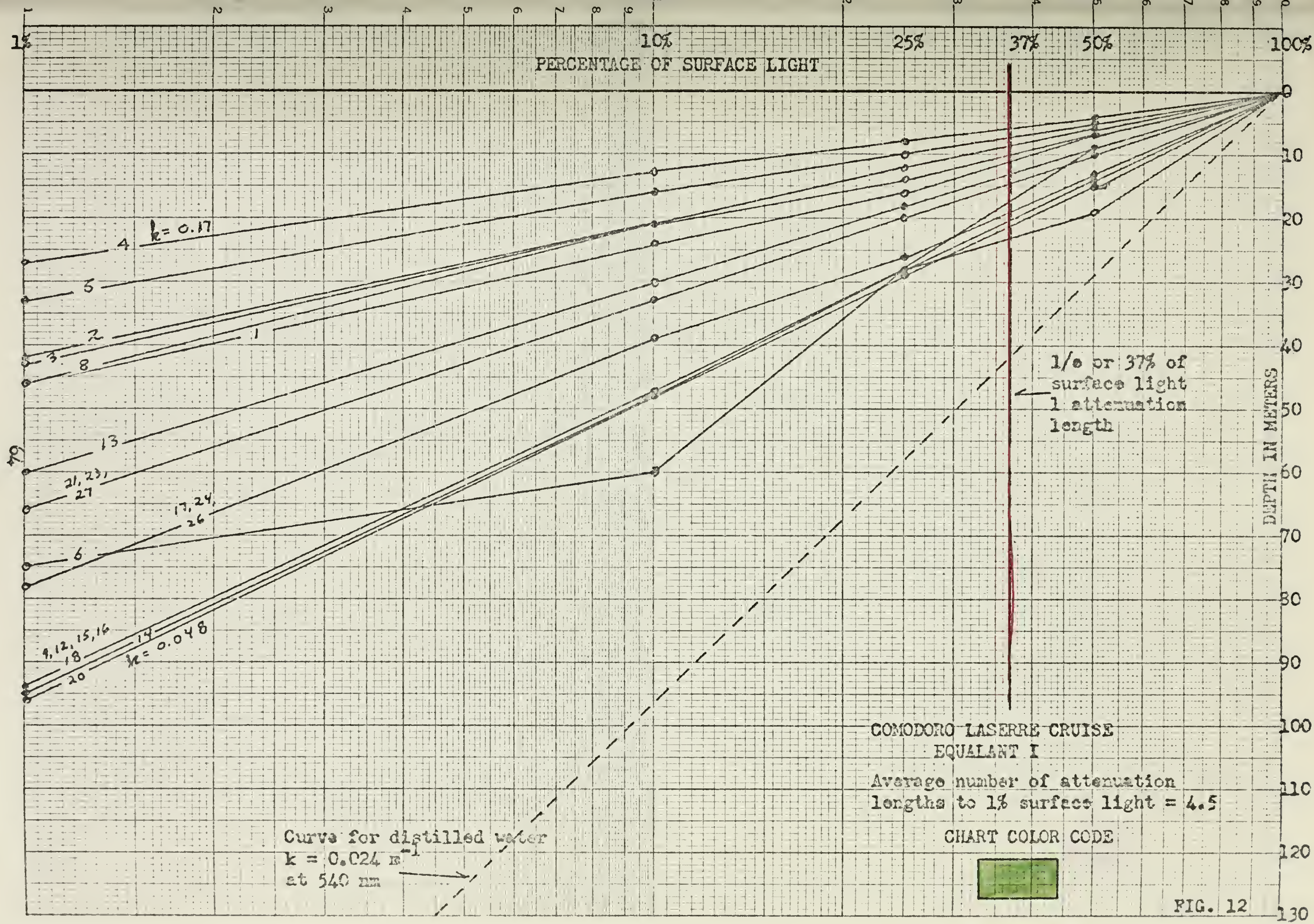
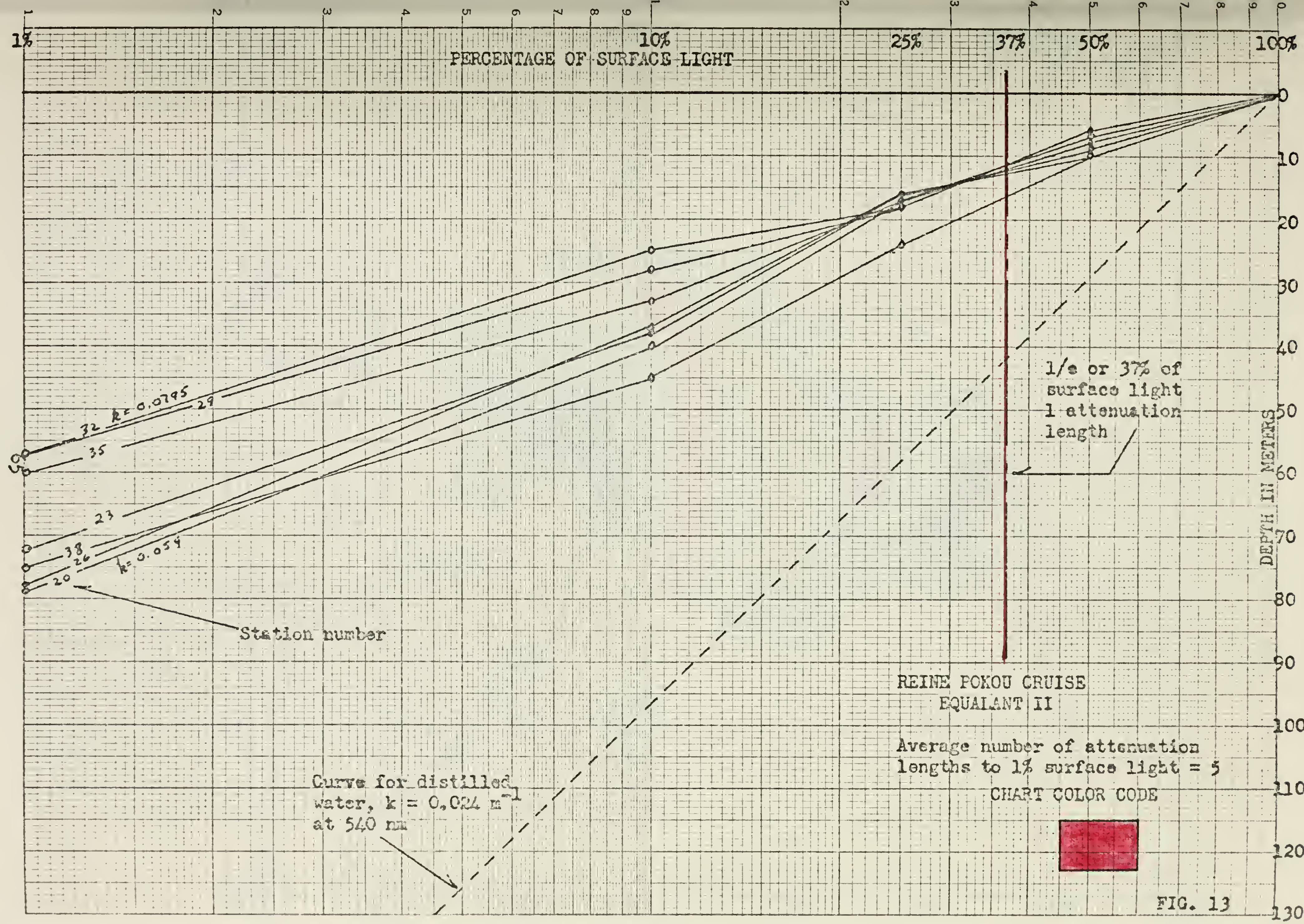

1%
10%
25%
37%
50%
100%
PERCENTAGE OF SURFACE LIGHT
DEPTH IN METERS
k = 0.17
k = 0.048
4
5
2
3
1
8
13
21, 23, 27
17, 24, 26
6
4, 12, 15, 16, 18
14
20
1/e or 37% of surface light
1 attenuation length
COMODORO LASERRE CRUISE
EQUALANT I
Average number of attenuation lengths to 1% surface light = 4.5
CHART COLOR CODE
Curve for distilled water
$k = 0.024\ m^{-1}$
at 540 nm

FIG. 12



1%
10%
25%
37%
50%
100%
PERCENTAGE OF SURFACE LIGHT
DEPTH IN METERS
0
10
20
30
40
50
60
70
80
90
100
110
120
130
k= 0.0795
29
32
35
23
38
26
20
k= 0.059
Station number
1/e or 37% of surface light
1 attenuation length
REINE POKOU CRUISE
EQUALANT II
Average number of attenuation lengths to 1% surface light = 5
CHART COLOR CODE
Curve for distilled water, k = 0.024 m⁻¹ at 540 nm

FIG. 13

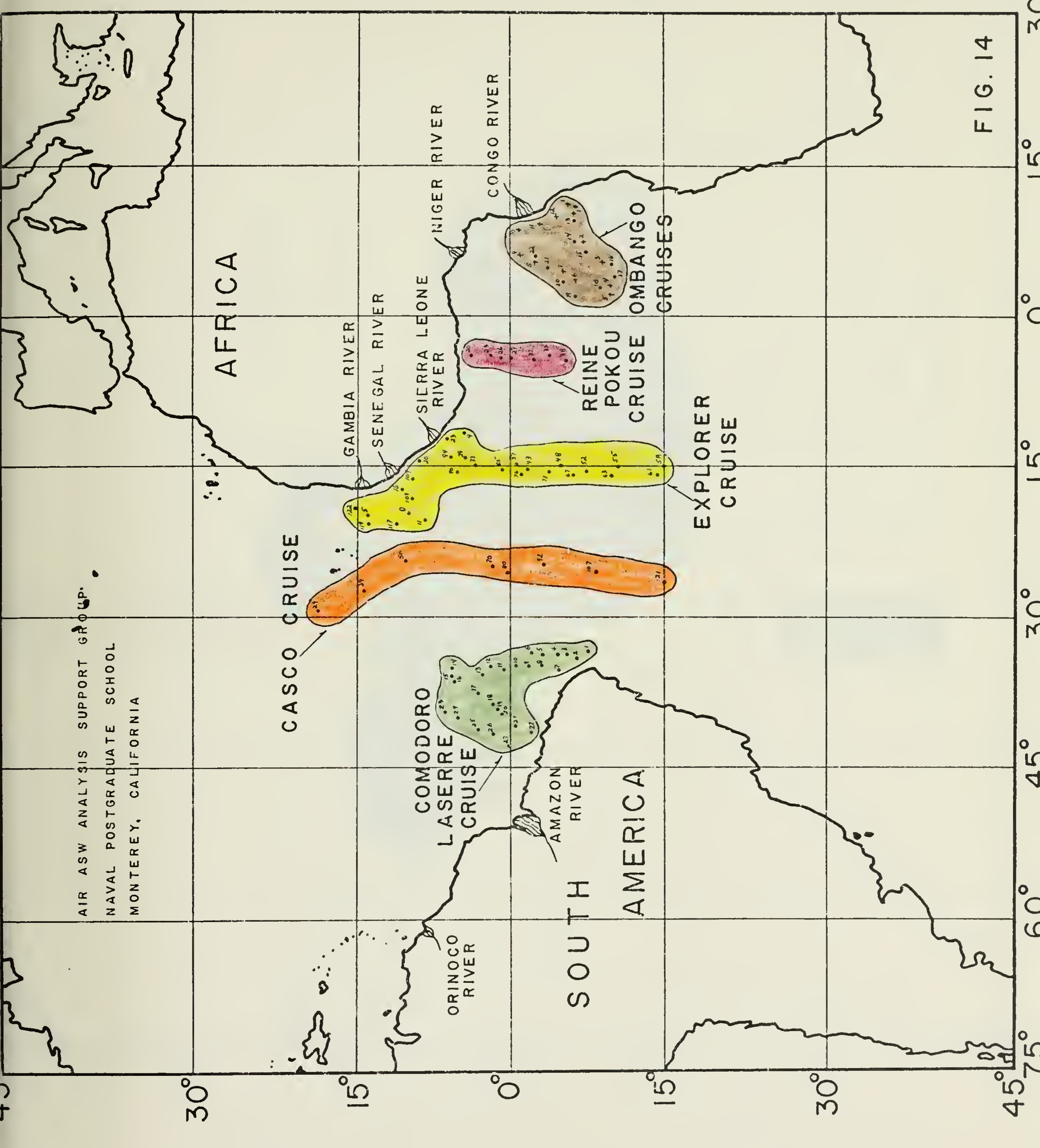

AIR ASW ANALYSIS SUPPORT GROUP.
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA
AFRICA
SOUTH AMERICA
GAMBIA RIVER
SENEGAL RIVER
SIERRA LEONE RIVER
NIGER RIVER
CONGO RIVER
AMAZON RIVER
ORINOCO RIVER
OMBANGO CRUISES
REINE POKOU CRUISE
EXPLORER CRUISE
CASCO CRUISE
COMODORO LASERRE CRUISE
30°
15°
0°
15°
30°
45°
75°
60°
45°
30°
15°
0°
15°
30°

FIG. 14

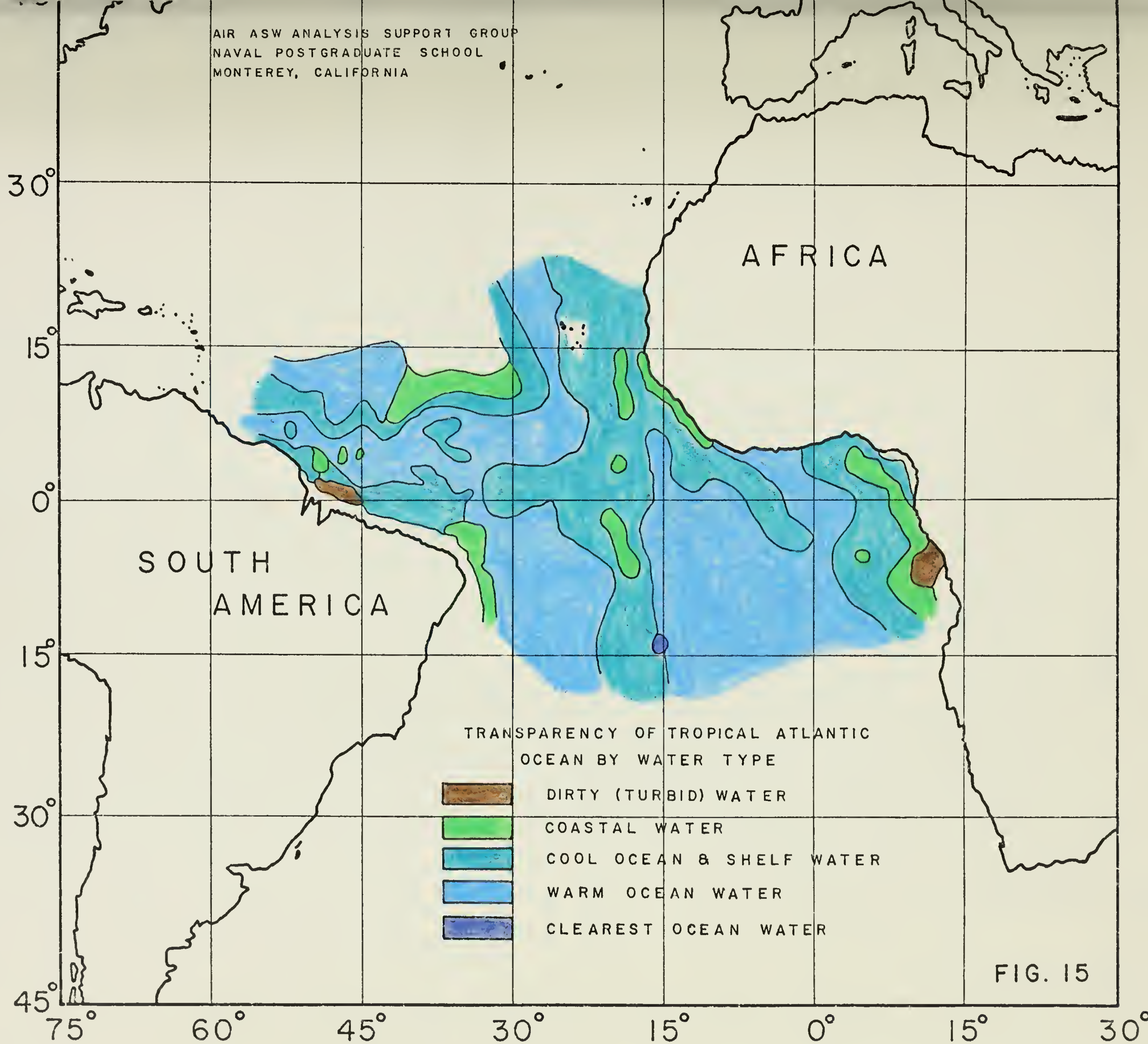

AIR ASW ANALYSIS SUPPORT GROUP
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA
AFRICA
SOUTH
AMERICA
30°
15°
0°
15°
30°
45°
75°
60°
45°
30°
15°
0°
15°
30°
TRANSPARENCY OF TROPICAL ATLANTIC
OCEAN BY WATER TYPE
DIRTY (TURBID) WATER
COASTAL WATER
COOL OCEAN & SHELF WATER
WARM OCEAN WATER
CLEAREST OCEAN WATER

FIG. 15

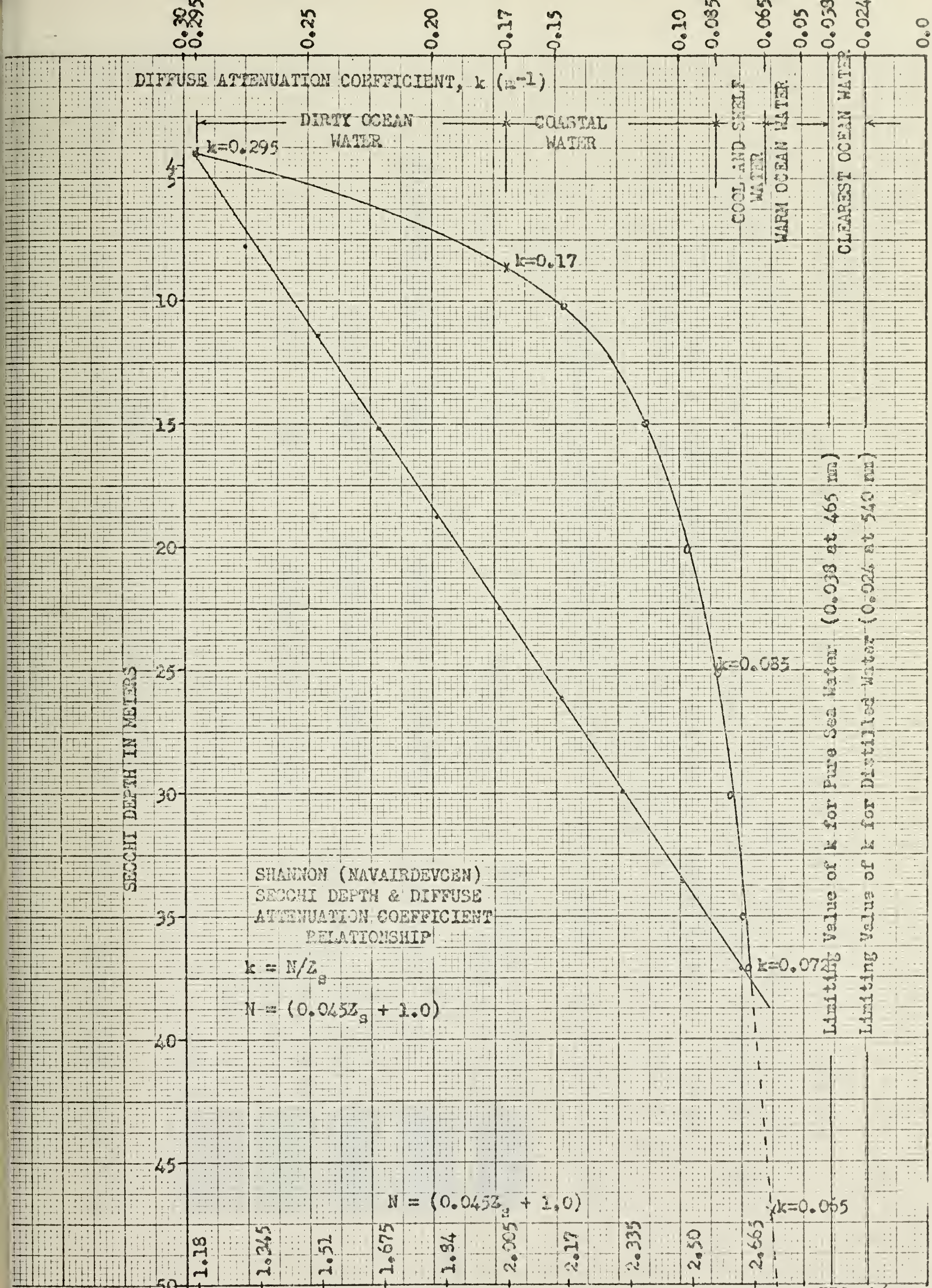

0.30
0.295
0.25
0.20
0.17
0.15
0.10
0.085
0.065
0.05
0.038
0.024
0.0
DIFFUSE ATTENUATION COEFFICIENT, k (m-1)
DIRTY OCEAN WATER
COASTAL WATER
COOL AND SHELF WATER
WARM OCEAN WATER
CLEAREST OCEAN WATER
k=0.295
k=0.17
k=0.085
k=0.072
k=0.065
SECCHI DEPTH IN METERS
4
10
15
20
25
30
35
40
45
50
SHANNON (NAVAIRDEVCEN)
SECCHI DEPTH & DIFFUSE
ATTENUATION COEFFICIENT
RELATIONSHIP
k = N/Z s
N = (0.045Z s + 1.0)
N = (0.045Z s + 1.0)
1.18
1.345
1.51
1.675
1.84
2.005
2.17
2.335
2.50
2.665
Limiting Value of k for Pure Sea Water (0.038 at 465 nm)
Limiting Value of k for Distilled Water (0.024 at 540 nm)

FIG. 16a

COLOR	WATER TYPE	DIFFUSE ATTEN. COEFFICIENT, $k\,(m^{-1})$	EQUIVALENT SECCHI DEPTH, Z_s (m)
	DIRTY WATER	>0.17	4 - 8
	COASTAL WATER	0.17 - 0.085	8 - 25
	COOL & SHELF WATER	0.085 - 0.065	25 - 37
	WARM OCEAN WATER	0.065 - 0.04	SEE NOTE BELOW
	CLEAREST OCEAN WATER	<0.04	" " "

Z_s - CALCULATED BY USING THE SHANNON RELATIONSHIP (NAVAIRDEVCEN):

$$N \approx 0.045\,Z_s + 1.0$$

N IS THE CORRELATION FACTOR AND IS APPROXIMATELY CORRECT FOR THE RANGE: $4m \leq Z_s \leq 37m$. THE RELATIONSHIP FOR N AND k IS: $k = N/Z_s$

k IS INTEGRATED OVER THE DEPTH WHERE THE LIGHT INTENSITY DECREASES TO 1% OF THE SURFACE LIGHT INTENSITY. SUN & SKY LIGHT IS THE SOURCE OF LIGHT MEASURED BY THE PHOTOMETER.

FIG. 16b

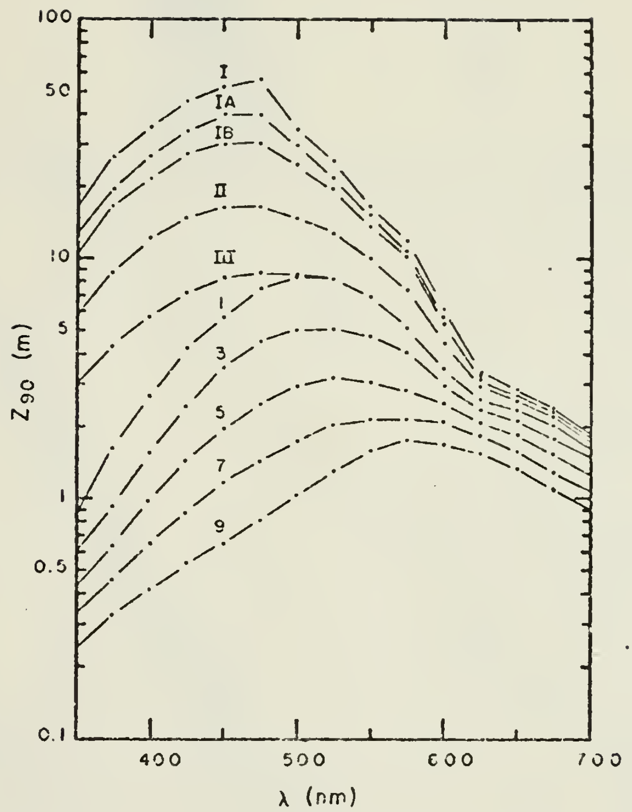


Fig. 4. Variation of z_{90} with wavelength for various water types given by Jerlov in Ref. 9.

Fig. 17

Graph from: H. R. Gordon & W. R. McCluney, "Estimation of the Depth of Sunlight Penetration in the Sea for Remote Sensing", Applied Optics, Vol. 14, No. 2, February 1975, Page 413-416.

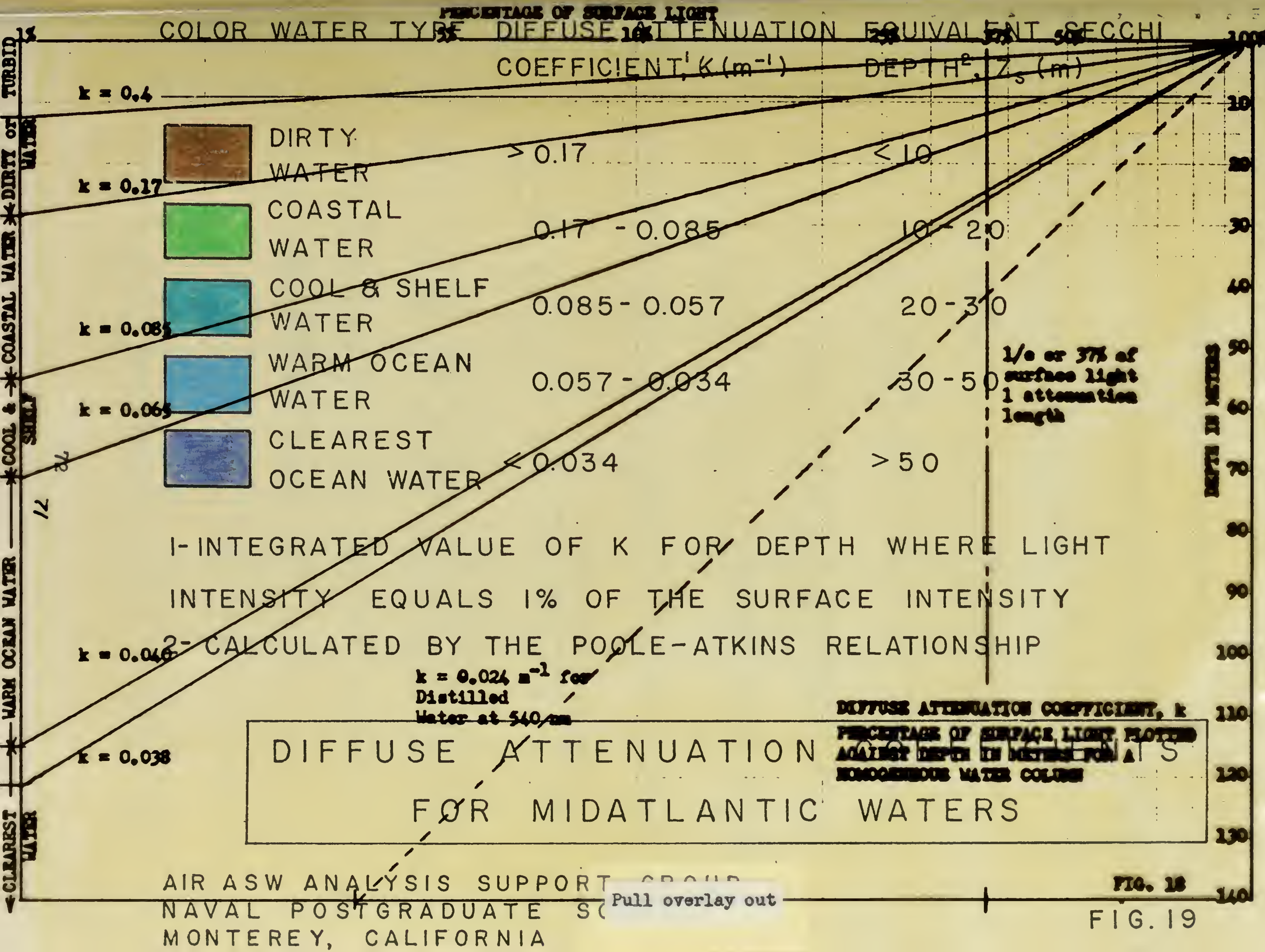

PERCENTAGE OF SURFACE LIGHT
1%
5%
10%
25%
37%
50%
100%
COLOR WATER TYPE
DIFFUSE ATTENUATION COEFFICIENT[1] K (m^{-1})
EQUIVALENT SECCHI DEPTH[2], Z_s (m)
DIRTY WATER
> 0.17
< 10
COASTAL WATER
0.17 - 0.085
10 - 20
COOL & SHELF WATER
0.085 - 0.057
20 - 30
WARM OCEAN WATER
0.057 - 0.034
30 - 50
CLEAREST OCEAN WATER
< 0.034
> 50
1- INTEGRATED VALUE OF K FOR DEPTH WHERE LIGHT INTENSITY EQUALS 1% OF THE SURFACE INTENSITY
2- CALCULATED BY THE POOLE-ATKINS RELATIONSHIP
k = 0.4
k = 0.17
k = 0.085
k = 0.065
k = 0.046
k = 0.038
$k = 0.024\ m^{-1}$ for Distilled Water at 540/nm
1/e or 37% of surface light 1 attenuation length
DEPTH IN METERS
10
20
30
40
50
60
70
80
90
100
110
120
130
140
TURBID
DIRTY or WATER
COASTAL WATER
COOL & SHELF
WARM OCEAN WATER
CLEAREST WATER
DIFFUSE ATTENUATION COEFFICIENT, k
PERCENTAGE OF SURFACE LIGHT PLOTTED AGAINST DEPTH IN METERS FOR A HOMOGENEOUS WATER COLUMN
DIFFUSE ATTENUATION COEFFICIENTS FOR MIDATLANTIC WATERS
FIG. 18
AIR ASW ANALYSIS SUPPORT GROUP
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA
Pull overlay out
72
71

FIG. 19

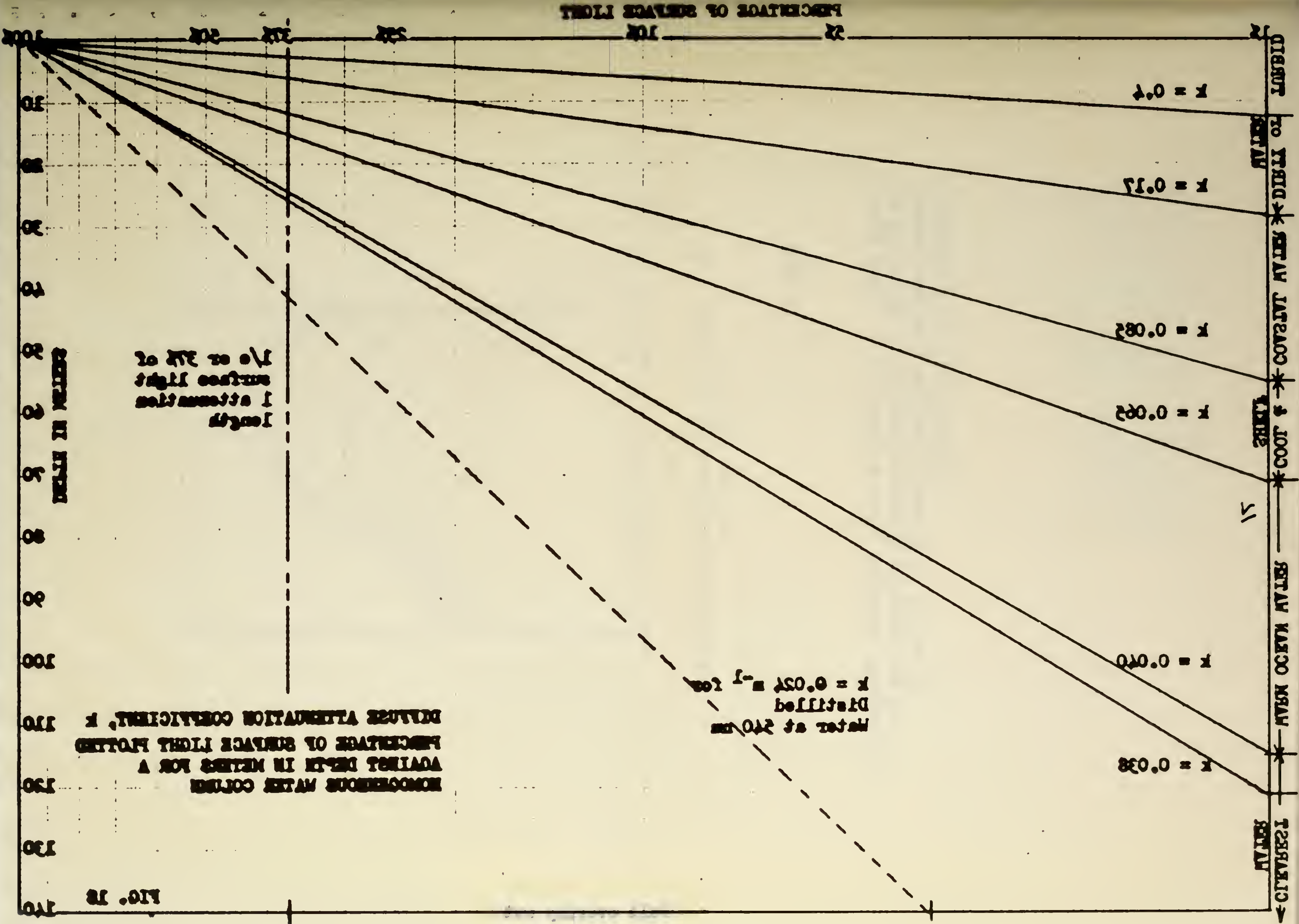

PERCENTAGE OF SURFACE LIGHT
DEPTH IN METERS
DIFFUSE ATTENUATION COEFFICIENT, k
PERCENTAGE OF SURFACE LIGHT PLOTTED
AGAINST DEPTH IN METERS FOR A
HOMOGENEOUS WATER COLUMN
1/e or 37% of
surface light
1 attenuation
length
k = 0.024 m⁻¹ for
Distilled
Water at 540 nm
k = 0.4
k = 0.17
k = 0.085
k = 0.065
k = 0.040
k = 0.038
TURBID
DIRTY or WATER
COASTAL WATER
COOL & SHELF
WARM OCEAN WATER
CLEAREST WATER

FIG. 18

COLOR	WATER TYPE	DIFFUSE ATTENUATION COEFFICIENT[1], K (m^{-1})	EQUIVALENT SECCHI DEPTH[2], Z_s (m)
	DIRTY WATER	> 0.17	< 10
	COASTAL WATER	0.17 - 0.085	10 - 20
	COOL & SHELF WATER	0.085 - 0.057	20 - 30
	WARM OCEAN WATER	0.057 - 0.034	30 - 50
	CLEAREST OCEAN WATER	< 0.034	> 50

1- INTEGRATED VALUE OF K FOR DEPTH WHERE LIGHT INTENSITY EQUALS 1% OF THE SURFACE INTENSITY

2- CALCULATED BY THE POOLE-ATKINS RELATIONSHIP

DIFFUSE ATTENUATION COEFFICIENTS FOR MIDATLANTIC WATERS

AIR ASW ANALYSIS SUPPORT GROUP
NAVAL POSTGRADUATE SCHOOL
MONTEREY, CALIFORNIA

FIG. 19

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26 Ltr from Mr. John Shannon, NAVAIRDEVCEN to Prof W. P. Cunningham, 6 Dec 1974, Ser 202209.

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